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Acoustic Emissions Tree Monitoring System

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FINAL REPORT

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TEAM 4

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ABSTRACT

Trees play an essential role of providing oxygen and taking in the increasing carbon dioxide in the atmosphere. They can live thousands of years, but their lives can be cut short due to unexplained circumstances. The Morton Arboretum's Center for Tree Science speculates that acoustic emissions (AE) can help resolve these mysteries by detailing and quantifying the stress waves inside a tree to better understand the health and well-being of trees. For this goal, an electrical circuit and accompanying mechanical housings were designed to support an AE sensor. The AE sensor system was tested in Northern Illinois University's Digital Signal Processing Lab's anechoic chamber. During testing, the system recorded three distinct responses from each mode of testing. While the device displayed an ability to serve as a platform to collect AE readings, improvements to the mechanical housing for eventual long-term deployment and expansions to the circuit to support more detailed data collection methods can be made.

1. INTRODUCTION

1.1 Background

Acoustic emission is a phenomenon of radiation of acoustic waves in solids that occurs when materials undergo irreversible changes in its internal structure, be it elastic and plastic deformation [1]. For such irreversible changes to occur, the material must be subjected to external forces. It is this mechanical loading that produces structural changes that generate local sources of acoustic waves [1]. Waves generated as a part of AE are of interest in structural health monitoring and quality control. When monitoring AE during testing, it is possible to detect, locate, and characterize the damage done to the object under study. AE testing has been widely applied and studied in the industrial field, through concrete and metallic structures, metallic pressure vessels, pipelines, and composite aircraft structures, among many others [1].

Despite AE testing being prevalent in a plethora of industries, little research has been done in its application on living structures. Within the scope of this investigation, AE testing is sought to be done in two ways: actively and passively. Active AE testing involves an external force controlled by the system being applied to the tree and then studying its response. Passive AE testing involves listening to the structure and its response to naturally occurring stimuli. As part of passive testing, it is theoretically possible to listen to the tree as it undergoes its phenological processes through the developed AE system.

1.2 Purpose of the Project

An AE platform would allow researchers to monitor the structural health of trees and provides an opportunity to study physiological processes, such as growth or sap flow, from a new angle. Doing so could provide better insight on internal structural changes as the tree ages and record data on its changes through environmental occurrences. With more information, the client seeks to better monitor their older trees and address any health or structural issues as they arise. Similarly, it has relevance in studying physiological processes within the tree, such as plant-water relations or growth. This information will also assist in the management and development of their trees and their environment. Outside of the inner workings of plant life, the acoustic study of trees at Morton Arboretum presents the opportunity to study and measure trees' effectiveness as sound barriers to mitigate noise pollution from highways, industry, or other sources.

1.3 Previous Work Done by Others

AE testing has been applied to some physiological processes in trees. In one of those studies, AE testing is employed to monitor cavitation events in Japanese black pine as it becomes dehydrated [2]. The AE data correlated to changes in water potential in the specimen along with the susceptibility of tissue to cavitate in that range of water potential. From this work, it seems possible for an AE testing platform to produce meaningful data in physiological studies.

Similarly, there is a range of work exploring environmental acoustic recording. One of these works is a report by Michael Towsey and Liang Zhang titled "False-Colour Spectrograms of Long Duration Acoustic Recordings" [3]. This report considers an approach to help visualize and process long-duration audio recording across different scales of time. The result of the approach is a way to organize the acoustic energy in a recording and then produce false-color images that ultimately help facilitate navigation through long-duration environmental recordings. The work established by this report is beneficial to the validity of a similar approach in this project.

1.3.1 Existing Products

There are some tree-focused audio products that are commercially available. The TreeTalker was developed by Nature 4.0 SR Srl for similar purposes of tree health monitoring as this project [4]. It is a tree attachment device that has a combination of sensors. Those sensors being an IR radial growth sensor, spectrometer, and gyroscopic sensor. There is also wireless communication for sending data from device to an external server and a connector for a solar powered battery. With all these in combination, the TreeTalker can monitor water transport, tree diameter growth, quantity and quality of foliage, tree stability, and various temperature and humidity [4].

Another commercially available product is the AudioMoth made by Open Acoustic Devices [5]. It started as a research project from three PhD candidate students at the University of Southampton, England. It was designed to be a low-cost environmental acoustic logger. Instead of having a network of sensors, it only has a microphone hooked up to a microcontroller and listens to as well as records the environment. These recordings are saved onto a Secure Digital (SD) card in the device. It has often been used to listen to trees as well as caves [5].

1.3.2 Patent Search Results

No patents regarding an AE tree monitoring platform exist. However, there are patents that focus on forest sensor arrays and their deployment to help monitor soil conditions [6]. Sponsored by The Boeing Company, the deployment and management of a widescale forest monitoring system is insightful to developing an array of AE and acoustic devices for use by The Morton Arboretum in similar conditions.

1.4 Brief Overview of the Report

The next section of the paper discusses the project design and gives a detailed description of the project. In addition to providing overall information, it will also include the thought process behind the three alternative designs of this device and how the optimal design was decided. The optimal design section will entail all the different parts of the device and how they inter-connect. The third section will cover the various realistic constraints of the device, and the fourth section talks about safety issues. Section five discusses the impact of this project to engineering solutions, and the following section describes how this experience helps us build our technical skills, preparing us for the workforce. Following is the budget and timeline of this project. Finally, there is information on our individual contributions and the conclusion.

2. PROJECT DESIGN

ALTERNATIVE DESIGN #1

The housing consists of two pieces of 3D printed polypropylene. At the connection between the bottom and top portions of the housing is a gasket. The bottom portion has inlaid pressure-fit metal threads to accept screws for mounting the electronics. The top portion must be tall enough to accept the electronics mounted to the bottom piece of the housing. An opening for the microphone is surrounded by a rain hood to allow for clear recordings while also able to repel most of the water that would move down or across the outside of the housing. An elastic band is attached to the bottom portion of the housing and stretched out to fit the application point. The force from this elastic band should keep the housing flush to the application point. This method of support is beneficial for application to branches along the tree's length, but not for the tree's trunk. Since the elastic band is external to the tree and applied for a couple of weeks at a time, it should pose no threat to the health of the tree. The bottom section of the housing has hooks attached to the bottom that accept the elastic band, as shown in the figure below:

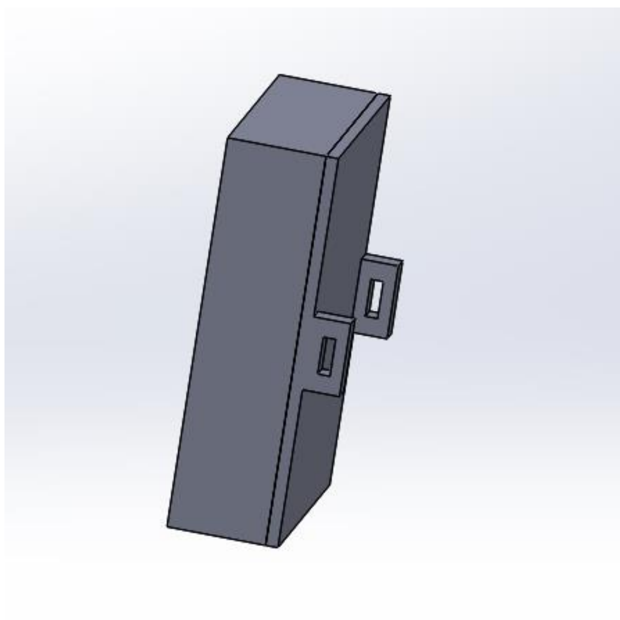


Figure 1. *Housing, Alternative Design 1*

For this design, the power source is only a relatively inexpensive lithium-ion (LiPo) battery comparing to the DeWalt lithium ion (Li-Ion) battery. This would be a good alternative if the power draw is lower than estimated, and this would be enough to power the system for a week. However, this is unlikely, and being part of the cheapest design would end in the cheapest result. As well as this could be dangerous, LiPo batteries are known to be hazardous and in an outdoor situation could cause fires or chemical leaks [7]. LiPo batteries are sensitive to low temperatures and would require insulation as part of the housing design to prevent failure and keep the battery within a safe operating temperature. The lack of solar power would also shorten the lifespan of each charge of the battery compared to the optimal design. However, the usage of LiPo batteries makes it easy to plug in the power sources with available and dependable plugs.

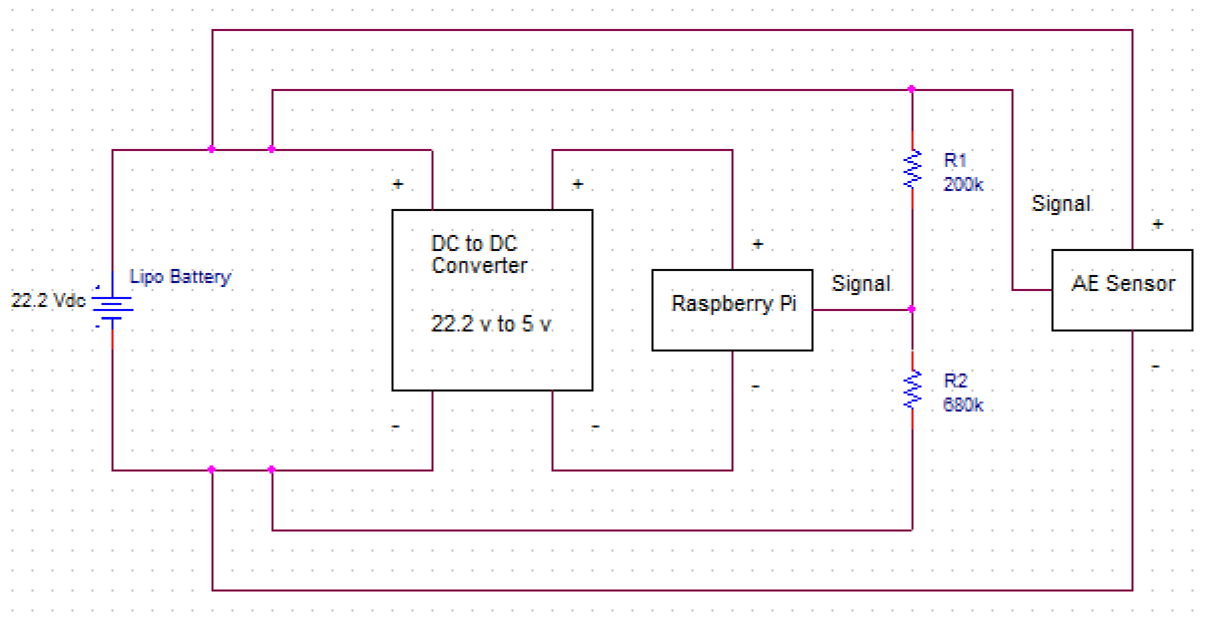


Figure 2. *Schematic of Alternative Design 1*

Moreover, the acoustic emission (AE) sensor is the only ecological sensor used. Since this is a bare minimum design, acoustic emission is the only type of data collection that would meet Morton Arboretum's needs. This design is in preparation that the project time constraint is short and only the absolute necessities can be accomplished. In addition, the microcomputer, Raspberry Pi, only has digital input signal pins [8]. Alone, it would not be able to support other ecological sensors that typically have an analog output signal anyway.

The specific sensor is the R.45I – Very Low Frequency AE Sensor with Integral Preamp [9]. Because there is an integrated preamplifier within this AE sensor, there is no need for that supporting component, making this an advantage over other AE sensors without a built-in preamp. This would add an extra component to the circuit and possible wire crimped connectors, which could leave room for human error. As seen in

Figure 2, the only supporting components for the AE sensor are the resistors to step down the voltage of the signal output. This is because the AE Sensor produces a 22.2 V signal, which matches its input voltage from the LiPo battery. The Raspberry Pi can only handle input signal voltages up to 5 V [8]. The easiest way to step down the voltage without losing too much of the signal would be through adding a voltage divider circuit. This consists of two resistors taking in the input voltage and producing an output voltage between the two resistors. The description of this can be seen in Figure 2. The resistor values of 200k ohms and 680k ohms were calculated using the voltage divider formula in eq. 1, and the standard types of resistors that can be easily obtained.

$$V_{out} = V_{in}\left(\frac{R_2}{R_1+R_2}\right) \text{ ---------------------- (eq. 1)}$$

This signal voltage is a common concern across all three of the alternative designs because all the AE sensor signals are 20 V, and microcontrollers and microcomputers typically cannot handle such a large input voltage.

In addition, when the Raspberry Pi is being deployed in the system, it cannot be powered off of 22.2 V without getting damaged [8]. Because of this, a DC to DC Buck Converter will take the 22.2 V from the LiPo battery and step it down to 5 V to power the Raspberry Pi [8].

As for the programming of the Raspberry Pi, it will have a Linux Operating System (OS) because it is the most lightweight [8]. The most prominent coding language of Linux is Python and Bash Scripting. Both would be used in combination of each other. Unfortunately, trying to install a Windows OS or Macintosh OS would take up a decent amount of storage space and require a lot of processing power that this microcomputer does not have.

ALTERNATIVE DESIGN #2

The housing consists of two pieces of 3D printed polypropylene. The bottom portion has inlaid pressure-fit metal threads to accept screws for mounting the electronics. The top portion must be tall enough to accept the electronics mounted to the bottom piece of the housing, and an opening for the microphone is surrounded by a rain hood. Any openings in the design will have gaskets to keep the body as watertight as possible. The housing is attached to the tree using tree attachment bolts (TABs). This attachment methods allows for application of the system at almost any point on the tree with great reliability and strength. The bottom half of the housing flares out past the width of the op housing with guiding holes in the corners to accept TABs during installation, as shown in the figure below:

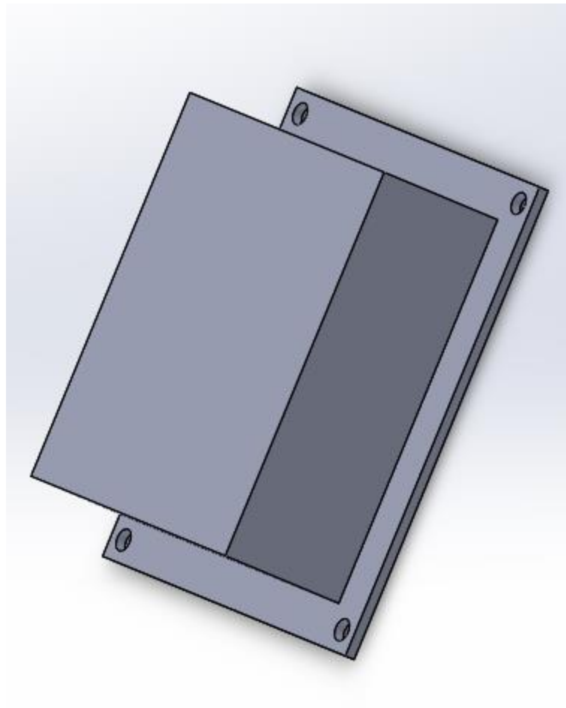


Figure 3. *Housing, Alternative Design 2*

TABs allow for flexible installation points anywhere along the tree that is wide enough to support it. The greater number of components increases the footprint of the device and adds more weight, requiring more substantial support. Once installed the bolts drive into the flesh of the tree and provides a direct, secure connection. But because the bolts are in the flesh of the tree, the tree is left with a thin, long wound.

DeWalt Li-Ion batteries are generally the higher quality option for this project, with expenses related to that. The prices for one of these batteries can be double that of a cheaper LiPo. However, these batteries are vastly different than their intended usage, and there would need to be significant rewiring. As a result of this rewiring, it would introduce new danger in that that any custom wiring on a power source is lower quality than one mass produced. In turn, this would likely offset the first advantage, higher price points meaning higher quality. There is also the built-in case for DeWalt batteries which would save in both time and money with less casing to build.

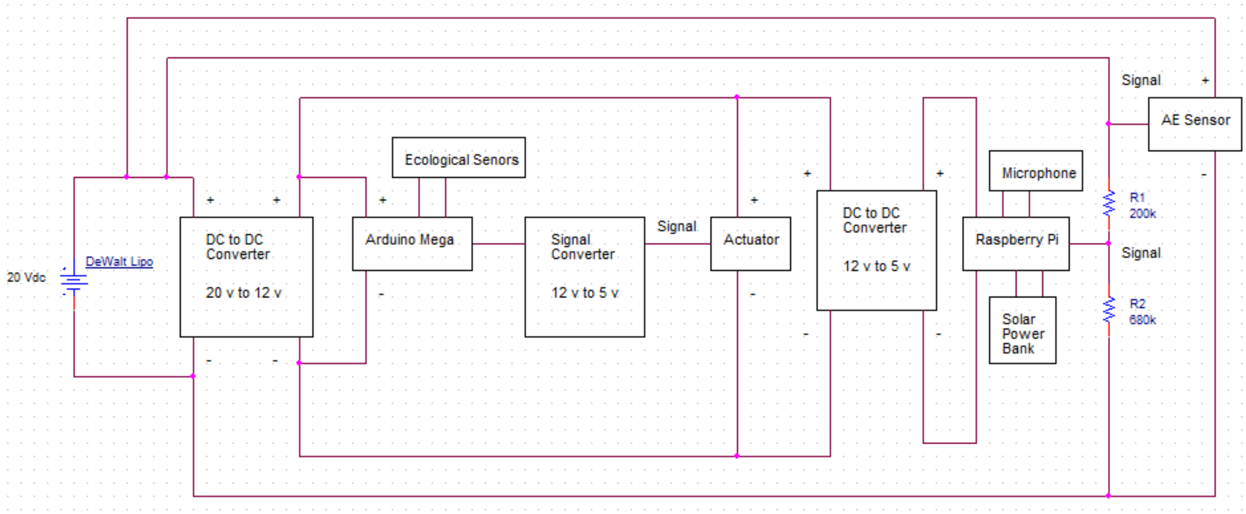


Figure 4. *Schematic of Alternative Design 2*

When comparing Figure 2 and Figure 4, the AE sensor wiring is setup the same way alongside the senor itself. The input power is between 20 to 30 V DC so, the DeWalt Lithium-Ion battery is still sufficient in this case [7]. The signal from the acoustic emission sensor will take in 20 V as well. Similarly, to the first alternative design, the signal will need to be stepped down to 5 V, so the input pin of the Raspberry Pi can handle it [8]. This is accomplished by the voltage divider circuit.

If this were not a time-constrained project, the priority of sensors would not focus only on acoustic emission. In addition to the acoustic emission sensor would be the microphone, accelerometer, vibration sensor and geophone. Ideally, it would be good to collect as much information as possible from different types of ecological sensors. The more data that can be obtained from a tree, the easier it will be to compare the circumstances later.

A microphone would be good for listening to sounds and air vibrations, so it would add an aspect for recording regularly audible sounds and their effects. This could include the impact woodpeckers have on trees' long-term health. As well, an accelerometer has benefits as a good as cheap additive for various strong vibrations. There is no major need for an accelerometer at the beginning stage of the project, but since this device is for a variety of research it would be a great asset in the future. However, this does mean that it is rather unnecessary for now, so it as added expense, but the cost is negligible.

The vibration sensor is good for detecting tree bark cracking. While this is not as responsive as the acoustic emission sensor, this would be a good opportunity to see how different the data collection process is. It produces an analog output [10], so it must be connected to the Arduino because of its ability to read an analog signal [11]. The operating voltage is from 3 to 5 V, which is what the Arduino can produce [11]. Therefore, it will be powered off the Arduino as well [11].

The geophone is great for picking up ground vibrations and picking up sounds from below ground, like from the roots of the tree. This could be universally useful since it would be this device’s only way to record anything of that magnitude.

For the computation side, both a Raspberry Pi and an Arduino will be utilized [8] [11]. With the new variety of sensors added to the circuit, the Raspberry Pi would not be able to read from an analog signal [8]. Therefore, seen in Figure 4, the Raspberry Pi will support the acoustic emission sensor and the microphone [8]. The rest of the sensors will be connected to the Arduino [11]. The Atmega2560 processor on the Arduino is only responsible for running scripts uploaded to it [11]. The scripts will be written in C++. Because the Arduino does not have the capability of storing data points, the data it takes in will need to be sent over to the Raspberry Pi [8] [11].The easiest way to do this is through hard wiring the two boards together. There is a chance that a different serial communication method could be explored, but as of now, this is the design plan.

The Linak LA12 linear actuator is used to force an active AE response from the tree. By producing an impulse force from its 750N max thrust and 40mm/s of extension speed [12], it is expected to produce an AE response different to that of its passive monitoring role. This actuator has its own 3D-printed two-piece polypropylene housing following similar standards as laid out above. This housing will also be supported using TABs.

ALTERNATIVE DESIGN # 3

Just as with the alternative designs 1 and 2, the housing consists of two pieces of 3D printed polypropylene. The bottom portion has inlaid pressure-fit metal threads to accept screws for mounting the electronics. The top portion must be tall enough to accept the electronics mounted to the bottom piece of the housing, and an opening for the microphone is surrounded by a rain hood. Any openings in the design will have gaskets to keep the body as watertight as possible. When applied to the application point on the tree, the housing will be nailed into the tree. For additional support, the housing is laid on an external post which is then anchored to the ground using three wires coming off the post from different angles, as shown below:

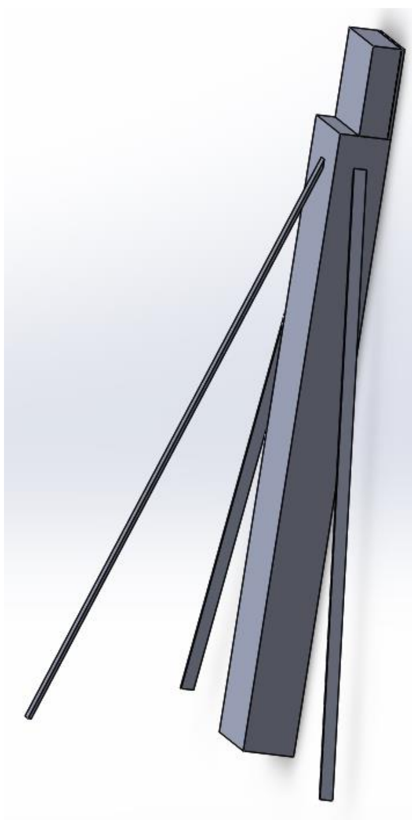


Figure 5. *Housing and support, Alternative Design 2*

The housing for this design is larger than in alternative design 1, but smaller than alternative design 2 since there are fewer components. However, the post results in a larger overall assembly. The post provides constant upwards support to the device but requires monitoring and adjustment during checkup every two weeks.

The combination of a LiPo battery and solar power charge the power would be reliable and rather long lasting. The LiPo battery works well with recharging plugs for solar power since it has built in charging capability. So, the solar power would offer an advantage in lifespan because it would regularly recharge the battery but not enough to be entirely self-sufficient. Although this would in the long term decrease the number of full recharges on the battery when it dies, this would be nullified by the constant recharge. This design would work rather well compared to other power sources, so it is currently the one in the optimal design plan. However, LiPo batteries are sensitive to low temperatures and would require insulation as part of the housing design to prevent failure and keep the battery within a safe operating temperature.

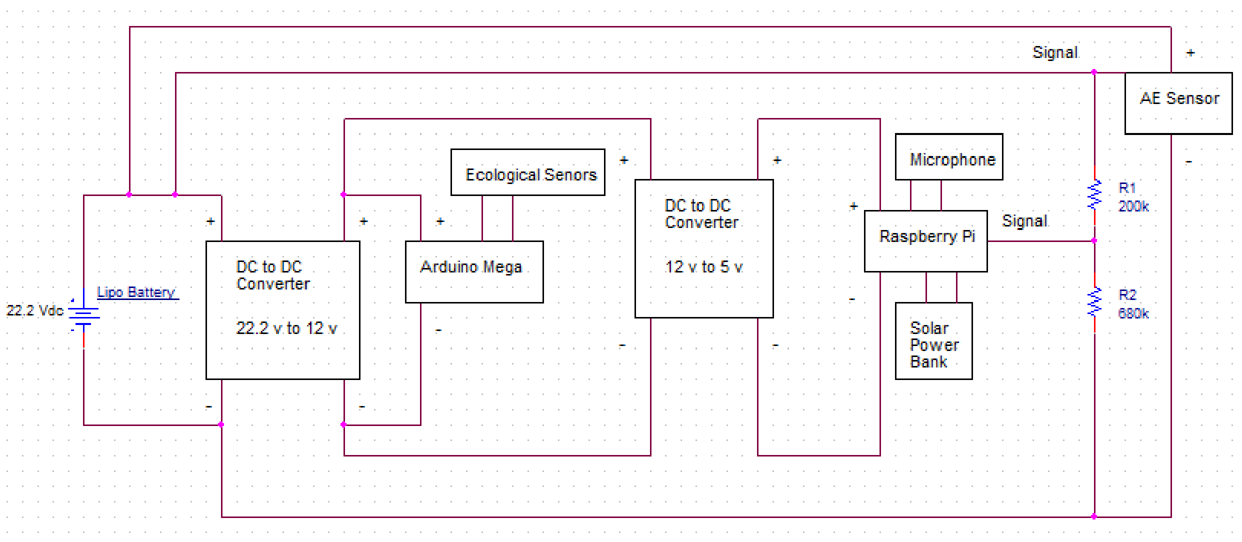


Figure 6. *Schematic of Alternative Design 3*

One of the major design differences between alternative design 2 and this one is the type of acoustic emission sensors used. Instead of the R.45I sensor, the design uses the Mini30S – 270-970 KHz Miniature AE Sensor with Integral Coaxial Cable [13]. The advantage to this one is the cost; it is said to be cheaper than the normal industrial acoustic emission sensors. The frequency is still in an appropriate range to collect data but not the ideal range. The disadvantage to this acoustic emission sensor is the lack of an integrated preamplifier, which is an essential component for steadying the raw signal. An external one would need to be picked out and attached to the signal wire of the AE sensor.

The Raspberry Pi and the Arduino would still be used in combination to support both the AE sensor and Microphone as well as the other ecological sensors, Accelerometer and Vibration Sensor [8] [11]. This is essentially a compromise of Alternative Design 1 and Alternative Design 2. The Arduino would be powered the same way, as seen in Figure 6, even with the change to a 22.2 V power supply [11]. Nonetheless, it will go through the DC-to-DC converter to be stepped down to roughly 12 V, the proper amount to power an Arduino [11].

The ecological sensors in this design are largely the same as the second alternative design but without a geophone. This is a likely situation since the only viable source of geophones is on backorder with no known date when this would stop. This situation would largely save money and not be incredibly damaging since the geophone is one of the more expensive components and only measures ground based vibrations. This would free up some room to make it more focused such as a higher quality AE sensor or ecological sensors.

CHOSEN DESIGN

The alternative designs listed here are in varying degrees of viability. The first alternative design is the bare minimum with cheap components, one that can be relied on in the event of something going wrong and running short on time. So it was not selected as the optimal design, the bare minimum is not necessary with time to spare. Instead, the decision was made to include some more cheaper components to supplement the main sections of the project.

The second alternative design is the maximum design, with as many components as could be put onto the project at once and the most expensive versions. This design has its strength in appealing to any needs that the client may have in mind for the future. However, this does mean it is unnecessarily large and complicated, not to mention adding to the price of each unit. Since it had many components that could be useful but were not necessary, the design was not chosen for the optimal plan.

The third alternative design is a mix of the two other designs, being a midpoint in too little and too many components. This alternative design has a few more sensors but and mostly good quality components while sacrificing some quality for price. This is the closest to the optimal design, with many of its components used. This was the design chosen for the optimal design.

When adapting the third alternative design to the optimal design a significant flaw was found, the Raspberry Pi drew around 500 mAh at its lowest point [8]. This means that it would drain the 8 Ah battery in around 16 hours at most and was unusable for its intended lifespan of one-week intervals. In order to adjust for this the Arduino was changed from a Mega to a much lower power Uno and the Pi was replaced with a data storage shield for the Arduino [8] [11]. Then some components were adjusted to fit the new boards and ended up simplifying the design. As a result, the optimal circuit had very little amp draw and the projected lifespan per recharge was able to match the client's lifespan requirements.

2.1 Optimal Design

2.1.1.1 Objective from the Fall

The modular platform is housed in a polypropylene shell containing a microcontroller, AE sensor, microphone, geophone, accelerometer, and a battery to power them. When the microcontroller is on, all sensors collect raw data and send it to onboard storage.

The client hopes to deploy this device on older maple and pine trees since older trees and those with structural defects are more likely to fail and cause damage to their surroundings [14]. While doing so, the device monitors the surroundings of the subject using the microphone and geophone in the device to provide recordings alongside any AE events. By collecting data from four sensors concurrently, the client hopes to correlate the physiological changes and state of the tree with events in its environment. They hope to deploy multiple devices across their land concurrently and monitor multiple trees and areas at the same time. When deployed, the clients hope to check on them and download the collected data every two weeks. To ensure the system lasts those two weeks, a solar panel is attached to the top portion of the housing and extends the life of the system.

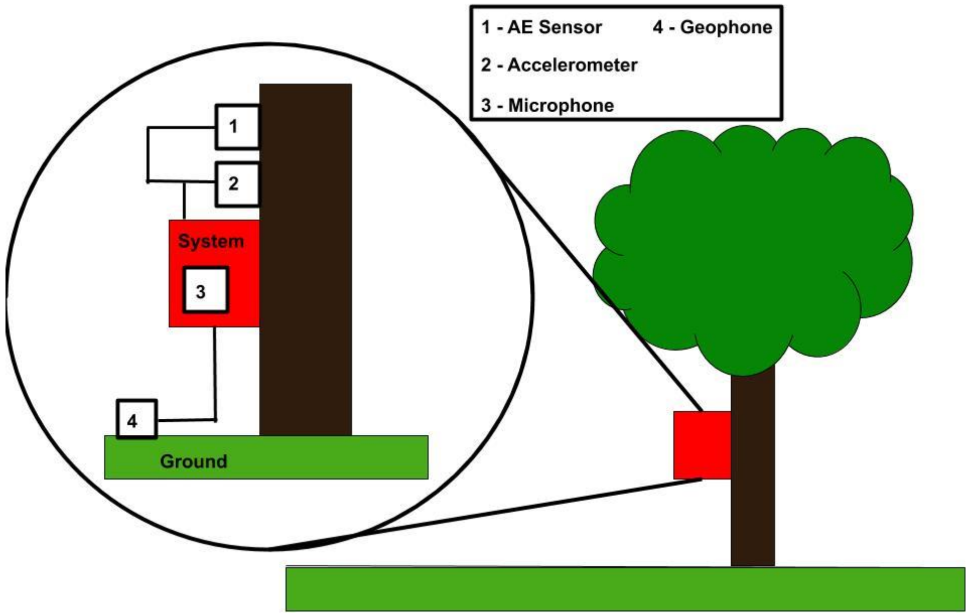


Figure 7. *Deployment of Monitoring System*

When deployed on a tree as in Figure 7, the housing is attached to the tree by an adjustable strap that wraps around the tree. This adjustable strap loops around rectangular cutouts in the bottom half of the housing and holds the device tight against the tree. These adjustable straps allow for flexible mounting points, be it on the tree's trunk or its branches. The AE sensor, accelerometer, and geophone are external to the housing, while the microphone is internal to the housing. The AE sensor, accelerometer, and their wires are routed outside of the housing and covered in foil to promote a water-resistant design and prevent tampering by local wildlife.

In use, the accelerometer and AE sensor are attached onto the flesh of the tree and both collecting the same type of frequency data, with the AE sensor being more precise. Since they both serve similar roles, the two are compared to determine differences in how they detect AE responses. If the response is similar during prototype testing, the accelerometer acts as a backup for the system in case the AE sensor fails.

Depending on its deployment point, the device is expected to monitor structural changes or the physiological development of a tree. By measuring acoustic waves produced by irreversible change in the structure, structural changes in that tree can be observed, prompting further action and evaluation. Additionally, the AE sensor can observe acoustic phenomena during sap flow if deployed to monitor the xylem of a tree.

As ecological sensors, the microphone and geophone are positioned to study different portions of a tree's environment. To facilitate recordings of the open air, an opening in the housing with a rain hood allows the microphone to collect sound from the environment. Focused on the roots of the tree, the geophone is deployed into the ground. To protect the wiring of the geophone, they are sleeved with a waterproof material.

2.1.1.2 Objective from the Spring

The objective of this project has shifted a bit since last semester. Due to time constraints, the client has agreed to make the project objective centered around the acoustic emissions sensor versus having it along with other ecological sensors. In addition, due to the covid pandemic, it has been difficult to get designs manufactured and 3D printed. Even if polypropylene is the best solution to making waterproof housing, typical polylactic acid (PLA) filament will have to suffice for the time being. Because of this, the device cannot be deployed outdoors without any supervision. It must be tested in a controlled environment.

2.1.2 Subunits

2.1.2.1 Mechanical Housings

The system is comprised of two 3-D printed housings: the electrical and AE sensor housings. The electrical housing holds the electrical circuit minus the AE sensor, while the AE sensor housing holds the AE sensor.

2.1.2.1.1 Electrical Housing

The electrical housing is a three-piece 3D printed polypropylene shell, consisting of the bottom, midpiece and top. Polypropylene is a heavily nonpolar polymer, which makes it inherently hydrophobic [15]. This property of polypropylene is ideal for developing a water-resistant system. Further enforcing the housing's water-resistant capabilities are gaskets employed at the interface between each part of the electrical housing. The top part of the housing accepts the solar panel, while the bottom half of the housing has press-fit metal threads to accept screws to secure down the microcontroller and buck converter. The midpiece has eight press-fit 4-40 threaded inserts, four on the top and bottom face of the midpiece for the bottom and top housing. The top housing is attached to the midpiece through four 7/16” 4-40 screws, while the bottom housing uses four 7/8” 4-40 screws.

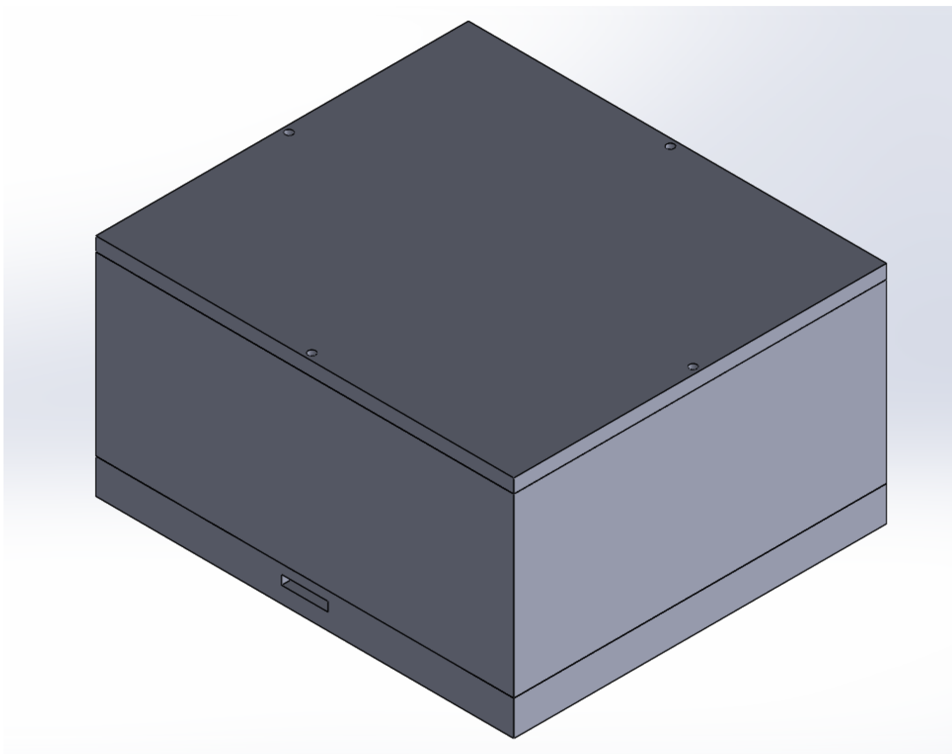


Figure 8. *Electrical Housing*

Holes to mount the solar panel are not yet modeled in the design but will be included after gaining insight during installation of the first prototype. Similarly, there is no feedthrough for the coaxial cable to connect to the microcontroller. Like the solar panel features, the design will be revised after the first prototype.

To test the water-resistant capabilities of the design, the electrical housing will be assembled without electronics and then sprayed with water multiple times, each test increasing in intensity. The first test is spraying the housing with water for 10 seconds, the second for 30 seconds, and every subsequent test for an additional 30 seconds. After each test, the housing will be disassembled, with the interior examined for water.

To allow for flexible installation points, the device is installed using a strap tightened around the tree. The strap is fed through a cutout on the bottom portion of the housing, as seen in figure 9:

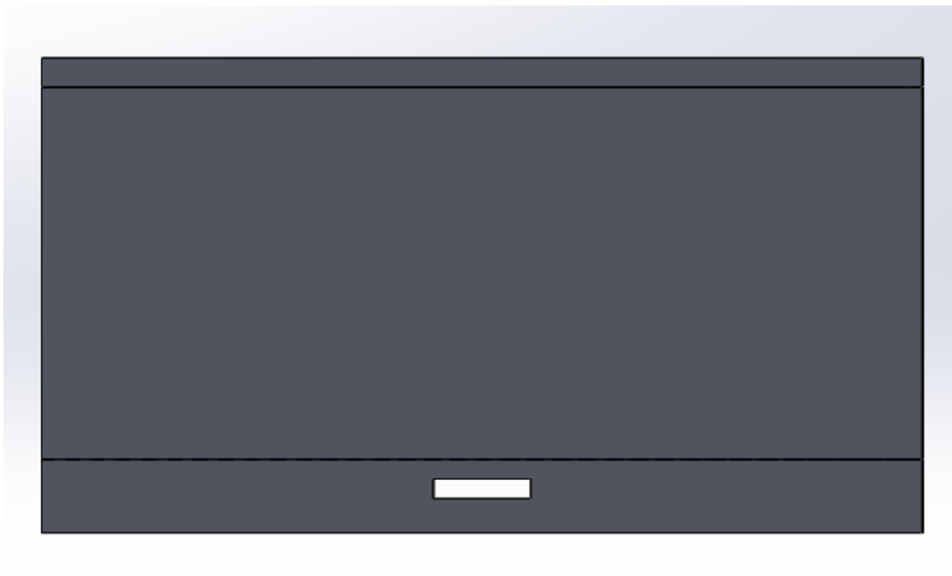


Figure 9. *Side View of Electrical Housing, Strap Cutout*

An adjustable strap allows for installation onto portions of a tree with differing thicknesses. In another alternative design, an external post with three cables tied into the ground. The external post offers excellent support but limits the installation point of the device near the bottom of the tree. The adjustable strap eliminates that limitation. Tree attachment bolts were also considered in another alternative design, but they cause damage to the flesh of the tree as they are drilled in. Adjustable straps do not damage trees in a similar manner. For all housing support mechanisms, they should be monitored and adjusted when the client goes out to collect data and check up on the machines.

No actuator will be present to force an active AE response. Very little research was found on the sort of AE response to expect from an impulse force on a tree. This lack of information makes it difficult to determine if the linear actuator detailed above in another alternative design is sufficient to produce a response of some discernible value. Instead, it is more valuable to focus on building a modular AE platform and then manually testing what kind of active AE response is produced.

2.1.1.2 AE Sensor Housing

The AE sensor housing serves to protect and acoustically isolate the AE sensor from its surroundings using neoprene foam. Made as a two-piece 3-D printed polypropylene shell, the AE sensor housing consists of a bottom and top portion.

The bottom portion of the AE sensor housing includes the bulk of the features of the AE sensor housing, detailed in figure 10 below.

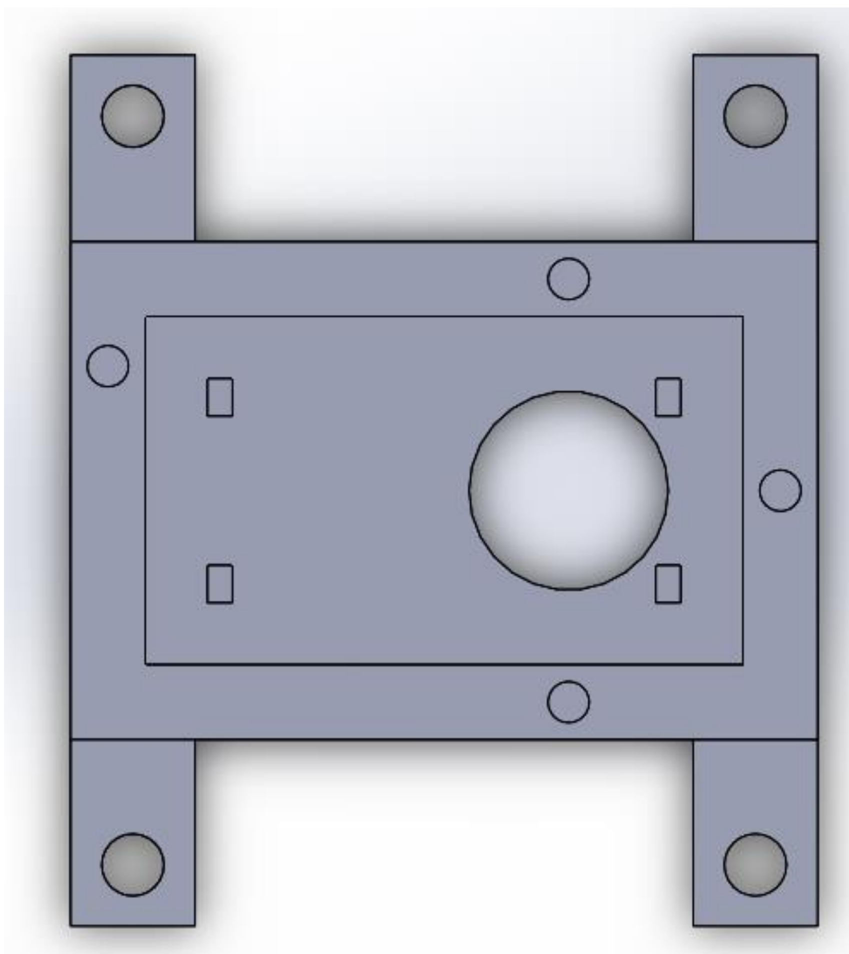


Figure 10. *AE Sensor Housing, Bottom*

These features include a cutout for the AE sensor through which the AE sensor contacts the surface of interest, four tabs to contain three ¼" neoprene sheets, a feedthrough hole for the coaxial cable that attaches to the AE sensor, and four 4-40 press-fit metal inserts.

The top portion of the housing includes holes through holes for screws that mate with the threaded inserts press-fit into the bottom portion. There is also a slight indent for which a piece of ¼” neoprene foam is to be taped, shown in figure 11 below.

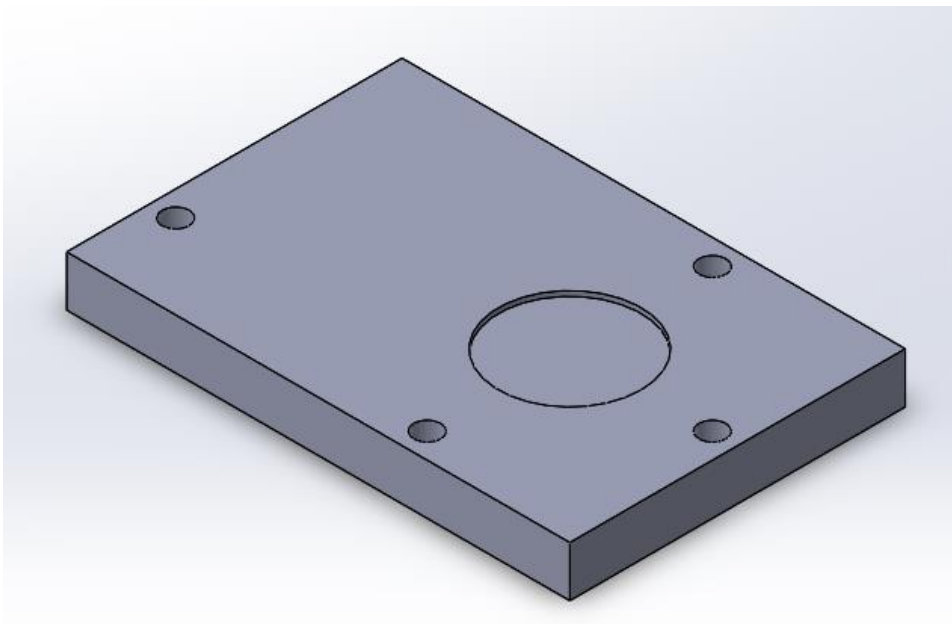


Figure 11. *AE Sensor Housing, Top*

In this configuration, when the top portion of the AE sensor housing is screwed into the bottom using four 7/16” 4-40 screws. When the top is tightened, the foam presses against the back of the AE sensor and provides a compression force to hold the sensor tight against the surface of interest. In this case, the top portion of the housing should be screwed into the bottom with the foam or indent facing towards the AE sensor.

2.1.2.2 Power

The most optimal type of battery cell for this project is the Lithium-Ion (Li-Ion) Battery versus other options being an Alkaline Battery and a Lithium-Polymer (LiPo) Battery. At a glance, the Li-Ion battery is pricier, being in the range of $70 to $150 for only one battery [7] whereas alkaline batteries are normally sold in packs and can be as cheap as a $1 [16], and LiPo batteries are from $30 to $160 [17]. The range of prices vary based on the amp hour discharge rate. A higher amp hour rate would result in a more expensive battery. However, Li-Ion batteries and LiPo batteries are rechargeable, and therefore, they have a cycle life, which is the number of times they need to be recharged after being fully discharged. On average both batteries last from 300 to 500 cycles [7] [17]. Alkaline batteries are only one-time use [16].

When comparing the shelf life of these two types of batteries, alkaline batteries have a shelf life of 3 to 5 years [16], LiPo batteries last up to 2 to 3 years [17], and Li-Ion batteries have a shelf life of up to 10 years [7]. This tree monitoring system is not in use for most of the year since its deployment starts in the spring and goes for a continuous three months. It is desired to have the product's lifespan aimed to last as long as possible. Having an alkaline or LiPo battery being left in the system for over half a year could be problematic if it starts to corrode. It is important that the system can be stored for long periods of time without any concern or need to check on it. Leaving a deteriorating battery in the system would damage the device otherwise. Because Li-Ion batteries have such a long shelf life, that would not be any concern soon of it going bad during storage.

In addition, when in use and depending on the discharge rate, generally, alkaline batteries get used up quicker than a Li-Ion and LiPo battery, especially with a power-hungry device such as this one. Eventually, the cost of buying alkaline batteries would exceed that of one Li-Ion battery.

Furthermore, the most demanding voltage requirement is for the AE sensor, and the battery needs to produce at least 20 V DC. There are very few alkaline batteries that can output that high of a voltage whereas Li-Ion and LiPo batteries were designed to power high voltage devices [7] [17].

Another consideration with the batteries is the operating temperature. The average range of Illinois spring weather is 0 °C to 26 °C [6]. LiPo batteries can operate in a temperature range of 0 °C to 50 °C [17] while Li-Ion batteries can operate in temperatures from 10 °C to 55 °C [7]. Since Li-Ion batteries cannot withstand the colder temperatures of spring, it would not be placed directly in the outdoor environment. The location of it is in the mechanical housing which is insulated to be most likely warmer than the outside. In addition, regardless of what battery is used, it would need to be deployed in the mechanical housing anyway due to it not being waterproof. If water were to come into contact with any of the batteries, there is a risk of a short circuit and possibility a fire.

The overall weight of the device is also something to watch for. This device should be light weight enough for one person to carry and deploy without any issues. However, the difference in weight between the LiPo battery and an Li-Ion Battery are negligible. As seen in Table 1, a LiPo battery weighs 815 grams and a Li-Ion battery weighs 907 grams [7] [17]. This is not deemed as a strain to carry for a typical adult.

Table 1: *Comparison of Glacier LiPo and DeWalt Li-Ion Battery* [7] [17]

	Glacier LiPo	DeWalt Li-Ion
Voltage	22.2 V	20 V
Capacity	8000 mAh	8000 mAh
Dimensions	106 x 47 x 47 mm	170 x 158 x 83 mm
Net Weight	815 g	907 g
Unit Price	$165.00	$148.00
Operating Accessories Price	$59.00	$41.00

Specifically, the DeWalt 20V Li-Ion battery is the choice of battery for this device. One of the desires by The Morton Arboretum is to have a system with a unit price of $100 to $500. In total, the DeWalt Li-Ion battery is cheaper being at $189 plus accessories as seen in Table 1 while the Glacier LiPo battery is at $224 in total. Furthermore, the long lifespan of the Li-Ion battery is worth it in a long run. In addition, a DeWalt battery has a plastic casing versus the Glacier LiPo battery has its cells exposed [7] [17]. The plastic casing helps contain the battery and not have it out in the open if something were to happen to it, making this the safer option.

The reasoning for an 8000 mAh DeWalt battery versus a lower Ampere hour battery is because another requirement by the client is to have the device be deployed for two weeks outdoors without any maintenance. As seen in Figure 8, only the Arduino Uno microcontroller and the AE sensor are connected to the battery [18]. The ampere draw for the Arduino Uno is 20 mA, and the ampere draw for the AE sensor is 25 mA [9] [18]. In total, the amp draw of the components is 45 mA. There are 336 hours in two weeks. By doing some simple algebra, this device would require a 15000 mAh battery in order to last two weeks. Because this form of battery does not exist as a DeWalt Li-Ion battery, the next best option would be to have the device deployed for one week with no maintenance. This requires an 8000 mAh battery, which is why this DeWalt battery was chosen.

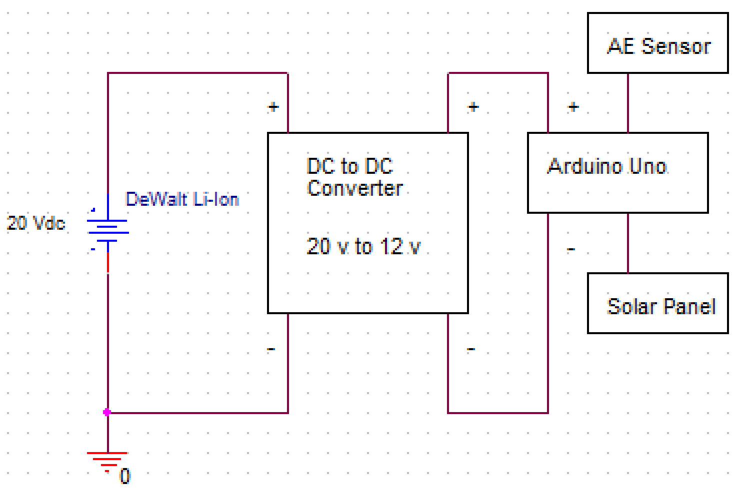


Figure 12. *Optimal Design Circuit*

As mentioned previously, the reasoning for a 20 V DeWalt Li-Ion battery versus any other voltage is because the AE sensor requires 20 V to be powered. This is the only component powered straight from the battery as seen in Figure 10. It will also be powering the microcontroller through a buck converter that will step down the 20 V to the correct voltage for these components.

2.1.2.3 Microcontroller

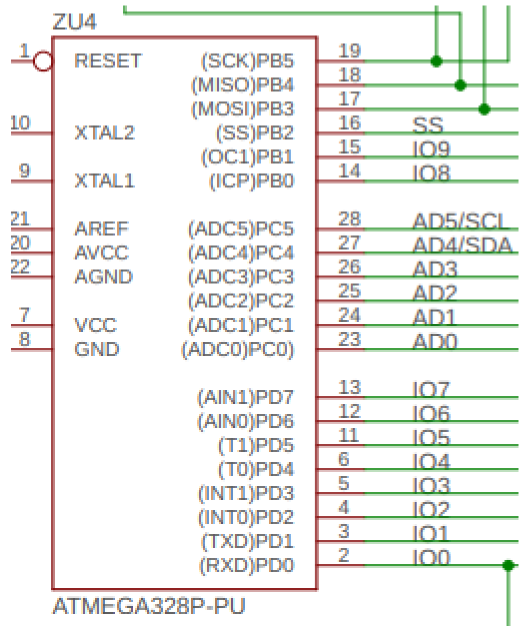


Figure 13. *Arduino Uno Pinout* [18]

The Arduino Uno is the microcontroller that is used in the optimal design. It is the desired choice comparing to other microcontrollers and microcomputers, such as the Raspberry Pi, because of its six analog signal input pins [8] [18]. These pins are critical for the usage of any components that produce an analog output signal, such as the acoustic emissions sensor. This is the reason why it is better to have this versus the Raspberry Pi microcomputer [8]. If the Arduino Uno were not included, the ecological sensors would have to be removed as well, which would make it difficult to add in modular to future iterations of this device [18]. The Raspberry Pi does not have any analog signal input pins [8]. From Figure 11 above, the analog signal pins are labeled as PC0 to PC5. All the input pins, regardless of analog or digital, on the Arduino can take in a 5 V DC signal [18]. Since this is what is produced by all the additional ecological sensors, any of the analog pins would work for the signal wire of the ecological sensors listed earlier.

In addition to analog input pins, there are fourteen digital signal input pins and six of them double up as pulse width modulation (PWM) signal input pins [18]. The digital pins are labeled as PD2 through PD7 and PB0 through PB5. PD0 and PD1 are technically digital signal pins as well, but they are mapped as the transmitter (TX) and receiver (RX) pins when the Arduino is connected to a computer via its Universal Serial Bus (USB) Type B port [18]. There are other digital input pins that have underlining functionalities from D10 through D13, but they are not necessary for this project. Currently, there will be no components producing a digital signal that would require the use of these pins. However, it is unclear whether the AE sensor produces an analog or a digital signal because the listing of it is not present on the datasheet [9]. Regardless, because the Arduino Uno has both analog and digital input pins, the device can easily be adjusted to take data from the AE sensor [18].

Another advantage to the Arduino Uno is the current draw being at 20 mA [18]. Because of the constraint of this device being outdoors as long as possible with a battery as a power source, it is critical to keep the amp draw from the components low. A microcomputer has a high amp draw that would drain the battery significantly faster. Specifically, the Raspberry Pi 4 has an amp draw of 600 mA [8].

Regarding all of the sensor data collected from the Arduino, the microcontroller itself cannot save the data [18]. The main purpose of one is to run the same script that controls a system continuously, not necessarily record data. However, there is an external Data Logging Shield for an Arduino Uno that can store the data collected in the form of a text file onto an SD card [19]. The circuit board comes assembled and attaches to the top of the microcontroller. When the client checks up on the device and needs to take the data, it is as simple as removing the SD card from the Data Logging Shield. For this project’s purposes, a 32 GB microSD is plenty of space for a text file that at most will be 5 KB large.

Typically, for powering a microcontroller for code testing purposes, it can simply be powered off a computer USB port using the appropriate cable. Because of the nature of this project, a computer cannot easily be deployed outdoors. Therefore, there is a different power supply for the Arduino [18]. The recommended input voltage to power an Arduino is between 7 to 12 V DC [18]. The absolute minimum voltage needed is 6 V DC, and the maximum voltage it can take is 20 V DC. While the DeWalt battery is rated for 20 V DC, it would not be ideal to power the Arduino off this [7]. The range beyond the recommended voltage has a higher chance of shorten the lifespan of the Arduino or cause it to not operate correctly after an extended period [18]. In addition, because this device is not being deployed in a controlled environment, it is difficult to tell when something with the microcontroller was to go wrong. The goal is to eliminate as many potential errors as possible. The same concept goes for the absolute minimum voltage and how it may cause Arduino Uno operation issues [18]. With that being said, a buck converter is used to step down the voltage from 20 V DC to 12 V DC. This way the Arduino can be powered and grounded from the buck converter without any operational concerns [18]. The external power is connected to pin 7, VCC (Voltage at the Common Collector). The ground connection is plugged into the GND (Ground), pin 8, on the Arduino [18].

In addition to having a Li-Ion battery power the Arduino Uno, there will also be a solar panel attached. There is a specific SparkFun Solar Panel that has a barrel plug adapter that can be directly plugged into the microcontroller [20]. The input barrel plug on the Arduino Uno can take in from 6 to 20 V, and this solar panel can produce up 6 V at 615 mA on a clear sunny day [20]. Even if it does not produce the maximum amount of voltage, the purpose of the solar panel is to have a backup power source in case the DeWalt battery were to drain faster than originally calculated. Furthermore, because our project is outdoors, it would be to this product’s advantage to use the sun in some form of solar power. The solar panel will be mounted on the outside of the mechanical housing.

In terms of operating temperature, the ATmega329P processor that runs the Arduino Uno has an operating temperature of -55 °C to 125 °C [21]. With the outdoor temperature range in Illinois during the springtime being from 0 °C to 26 °C [6], the Arduino will not have any issues operating in the constrained temperature conditions [18]. However, it is nowhere near waterproof and would cease to work as soon as water contacts the circuit board. Therefore, the Arduino is housed in the mechanical electronics box [18].

2.1.2.3.1 Programming

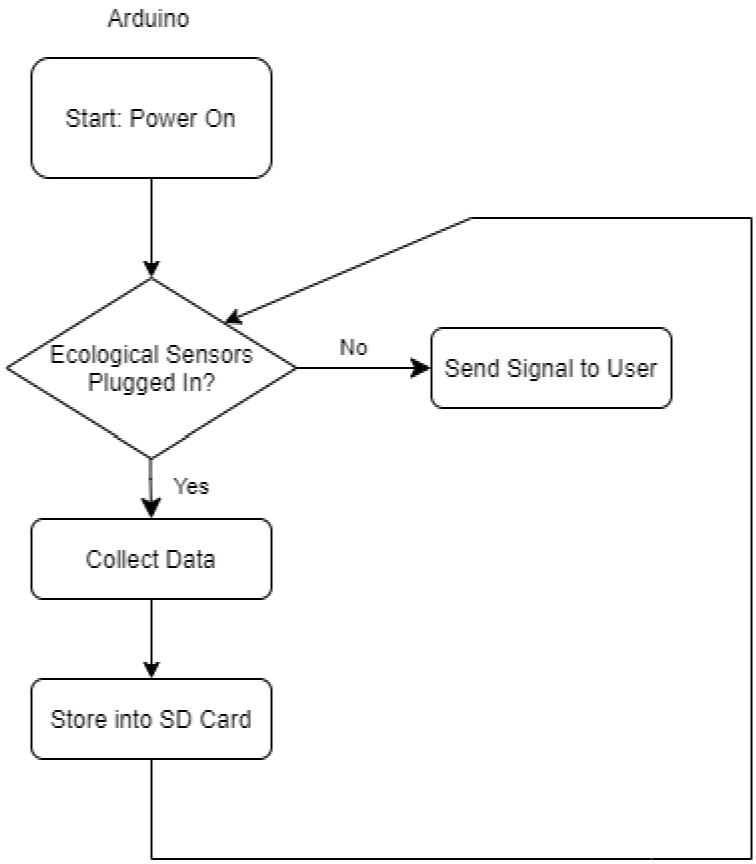


Figure 14. *Flow Chart Logic for the Arduino Uno* [18]

Figure 12 shows the logic behind how the Arduino microcontroller is programmed [18]. Once the device is turned on, there is a safety net in place checking if the ecological sensors turned on. If they are not powered on, due to an error, a signal is sent to the user possibly in the form of either a buzzer or an LED. If they are on as intended, then the Arduino starts running the sensors and collecting data [18]. Every couple of seconds, the data will be stored on the SD card. Another neat feature of the Arduino Data Logger Shield, there is a built-in Real Time Clock (RTC) [19]. The data that is stored onto the SD card will also have a timestamp on it, which helps correlate the data with the time of day. After, the program goes back to checking if the ecological sensors are plugged in, and the process starts over.

2.1.2.4 Acoustic Emission (AE) Sensor

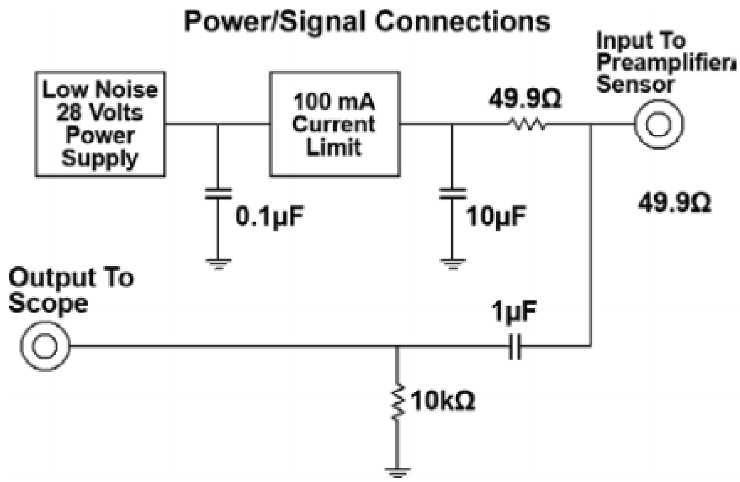


Figure 15. *Acoustic Emission Sensor Schematic* [9]

The acoustic emission (AE) sensor that is used for the optimal design is the F15a – High-Sensitivity Flat Frequency Response AE Sensor [22]. This is the better option versus Mini30S – 270-970K Hz Miniature AE Sensor with Integral Coaxial Cable for multiple reasons [13].

The frequency range for the F15a AE sensor is between 100 to 450K Hz [9], which is considered a high frequency. It is difficult to tell what specific frequency range is needed when it is not clear what could be listened for. However, the initial range that was decided on is between 20K and 300K Hz. This is because in an experiment involving acoustic emissions in trees and listening to the water flow within cavitation, this was the range of frequency used [23]. The Mini30S AE sensor has a frequency range of 270-970K Hz, which is way above the suggested range mentioned in the experiment [13].

Another point to note is that while the Mini30S AE sensor is small, 10 mm OD x 12 mm H, there is not a need for a sensor that small [13]. The size of the F15a AE sensor, 19 mm OD x 22.4 mm H, is still sufficient [23]. This is important for outside deployment, and the sensor will be located somewhere in a crevasse of the tree trunk. The smaller it is the easier it will be to attach.

The material that both AE sensors are made of stainless steel [13] [23]. This is desirable because stainless steel can minimize electromagnetic interference (EMI). Because this project is operating outdoors, there is no guarantee that there would not be other frequencies interfering with our data, making stainless steel a good choice.

For the F15a, there is an option to have a prebuilt in cable attached to the AE sensor too [23]. The connector of the AE sensor is a Bayonet Neill Concelman (BNC) connector [23]. This is convenient and saves time and effort to crimp a BNC connector onto a wire. It also reduces the change for human error if the connector is not crimped properly. The other end of this cable would be connected to the Arduino Uno for data collection [18].

This particular AE sensor is a passive device and does not need input voltage to work [23]. Therefore, it only has a singular cable that plugs directly into an analog signal pin on the Arduino.

The operating temperature for the F15a is -65 °C to 177 °C [23], which is well in range with the average Illinois spring temperature. Unfortunately, it is not waterproof and cannot be placed in the mechanical housing. The location of the AE sensor needs to be attached to the tree bark since its purpose is to listen to the structural health and water flow of the tree. The solution is to create a small housing for the AE sensor to reside in. This housing will be insulated and help reduce the external noise that may be happening around the tree.

Figure 16. *AE Sensor Housing*

As for physically attaching the AE sensor to the tree bark, it will do so through a nail that is hammered into the tree. Then the AE sensor will be taped onto the nail head with its housing covering the whole structure. The nail helps the AE sensor listen for vibrations inside the tree versus just on the surface.

2.1.2.5 Optional Ecological Sensors

As mentioned previously, due to the time restriction, other ecological sensors besides the AE sensor were not implemented. Below would have been the justifications for using the specific models of ecological sensors discussed.

The choice of microphone for this device is the SparkFun Electret Microphone. This microphone has three connections of power, ground, and signal, each easily wired onto the Arduino [18] [24] as seen in Figure 14. The main advantage to this microphone versus others is that it is the best for working with the Arduino's analog inputs. Alongside its inexpensiveness, where it reflects the pricing of being the optional component that it is, only there to supplement and assist the acoustic emissions sensor. These make this specific model of microphone helpful in listening to extraneous ecological noises and phenomena.

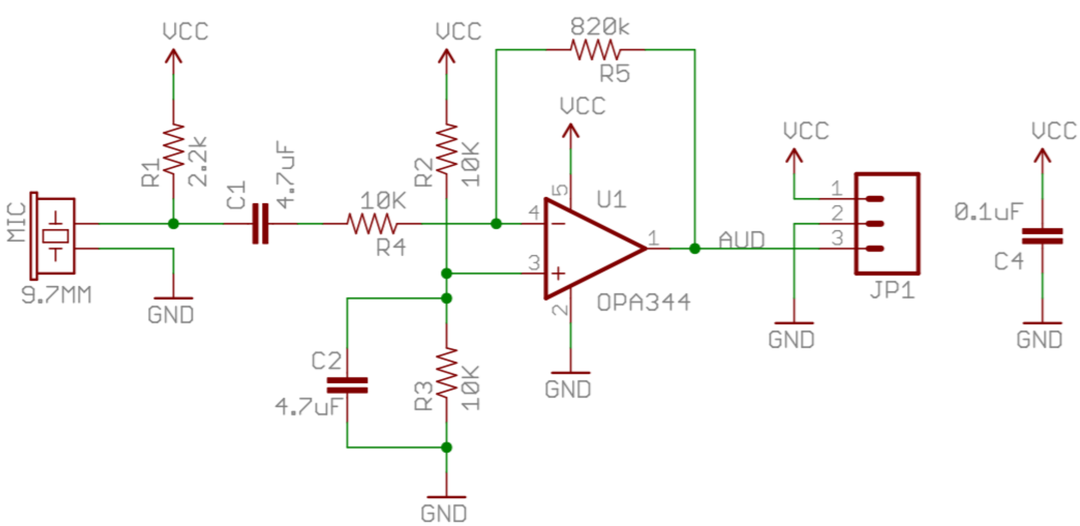


Figure 17. *SparkFun Electret Microphone Schematic* [24]

As for the continuous recordings surrounding the tree, this microphone could be a gateway to further research into identifying phenological acoustic patterns in a healthy tree. Being made of wood, trees are great conductors of sound. This could lead to discoveries in biodiversity, ecological dynamics, and new plant or animal activity. Otherwise, these recordings can be used as an outreach tool to teach the community how a tree actually "talks". The target recording frequency range is from hertz to potentially the kilohertz range, and this can be adjusted via the controlling software.

Another advantage is having a wide listening frequency range of 100-10000 Hz, which is very beneficial given that there is not a specific frequency range that needs to be aimed for at this point [24]. To narrow down a desired frequency, it requires experimental data collection to see what noises occur where on the frequency spectrum. The results will be more specific, and there is less likely to be noise interference from a distance, not coming from the tree.

Two concerns with the microphone are that it is not waterproof, and its cheapness. To address this, there is a waterproof covering that will cover the microphone during deployment. And on the second point, these microphones will easily be able to be tested before deployment and cheaply replaced if sub-par.

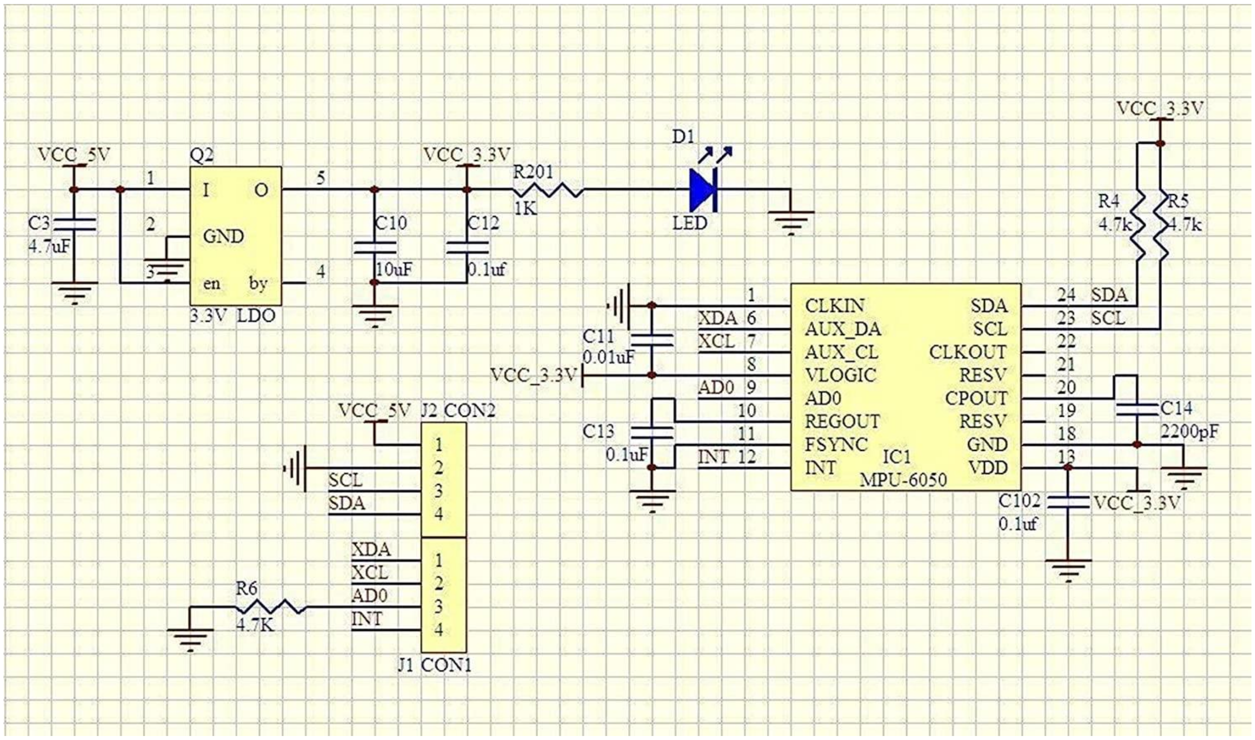


Figure 18. *Schematic of HiLetgo Accelerometer* [25]

In terms of additional ecological sensor priority goes, the primary interest is the accelerometer. A HiLetgo MPU6050 Accelerometer will be used in the optimal design for measuring vibrations [25]. The main purpose of the accelerometer to compare its data to the AE sensor, since it is said to be able to measure movement and vibrations in a mobile device. Then the data can be carefully examined, and sources of error can be removed. For instance, if a bug were crawling around the tree and walked over one sensor at a time, a sound would be heard on only one sensor but not the other. So, this simple device reduces sources of error by a large margin. This model was made specifically to connect to the Arduino and can only connect to the Arduino I/O pins because of its output analog signal [18] [25]. In Figure 15, it can be seen how the accelerometer is structured internally, with a different section spot for each section of the device. Pin 13 takes in power of 3.3V from the microcontroller, and pin 18 takes ground from the Arduino as well [25]. Pin 23 and 24 will be attached to the 3.3V as well. Pin 9 is the signal pin and can connect to any of the analog input pins on the Arduino [25].

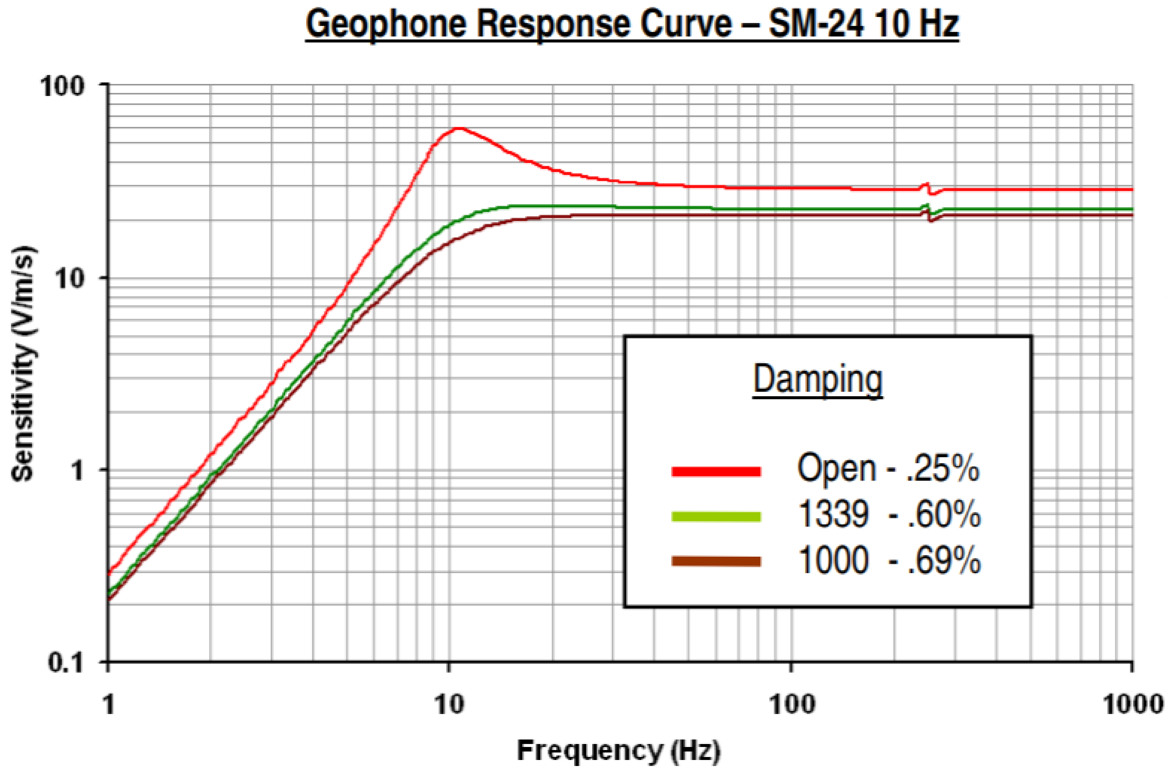


Figure 19: *Geophone Response Curve for the SparkFun SM-24* [26]

The secondary ecological sensor for this device is the SparkFun SM-24 geophone. This model specializes in sensing frequencies as low as 10 Hz as seen in Figure 16 [26]. This is very useful in collection of lower and subterranean sounds. The primary purpose of it is to listen into the tree's roots and any activity that may occur beneath the tree. While this does not add onto the primary goal of listening to the water flow throughout the tree, it does provide interesting insight into other information that can be useful. The wiring of the geophone is designed so that vibrations generate power, and the power level is sent back to the Arduino [26]. This also means that it puts less strain on the battery life and is an entirely passive component.

2.2 Prototype

The electrical housing prototype is 3-D printed PLA with a 20% infill, consisting of three individual parts: the bottom housing, midpiece, and top housing. The midpiece has eight press-fit 4-40 threaded inserts, four each for the bottom and top housing. The top housing is attached to the midpiece through four 7/16” 4-40 screws, while the bottom housing uses four 7/8” 4-40 screws.

The bottom piece has a 1” rectangular cut-out to accept an adjustable strap, and the top face of the bottom housing is meant for the electronics. To facilitate a more active approach of determining the position of the electronics, each piece of the circuit is attached to the bottom housing using double-sided tape for this round of prototyping. This proved to be a wise choice, as the circuit was re-arranged within the electrical housing multiple times, until the configuration shown in figure 22 was chosen.

Meant to connect the top and bottom potions of the electrical housing, the midpiece accepts the hardware from the top and bottom portions of the housing. In one of the walls of the housing, a hole was drilled during installation of the circuit to feed through a jumper from the microcontroller that is also soldered onto a coaxial cable that connects to the AE sensor.

Similarly, the top housing has holes that were drilled during installation of the solar panel. These on-site modifications to the housing serve to inform future iterations of the device and provide a more dynamic design framework.

When assembled, the electrical housing can contain the electronics and support its weight against the testing platform, as shown in figure 20 below.

Figure 20. *Electrical Housing Prototype, Installed on Testing Platform*

While the full weight of the electrical housing was supported by the adjustable strap, the housing did not sit flush against the testing platform. The weight of the Li-ion battery causes the housing to rotate. To rectify this issue and better distribute the weight of the device, the design will be modified to include two straps with two strap cutouts in the bottom housing.

The AE sensor housing prototype is 3-D printed PLA with a 20% infill, consisting of two individual parts: the bottom and top. The bottom has four press-fit metal inserts for which screws will mate through holes in the top. Neoprene foam is installed in the bottom and top of the AE sensor housing, providing noise isolation and additional compressive force, respectively.

The bottom of the AE sensor housing has three main features: tabs to hold sheets of ¼” neoprene foam, a cutout for the AE sensor, and a feedthrough hole for the coaxial cable.

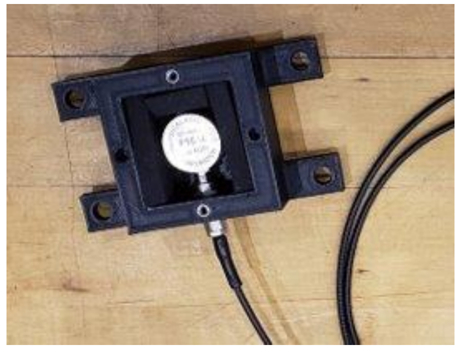


Figure 21. *AE Sensor Housing, bottom*

The prototype bottom fits all the components, but the coaxial cable does not connect to the AE sensor as well as was hoped. As such, the design has been revised for future iterations and was shown above in figures 10 and 11.

The final circuit design consisted of a battery, solar panel, switch, power rail, DC to DC buck voltage converter, microcontroller, and Acoustic Emissions (AE) sensor. There must be space above the battery for it to be slid into and out of.

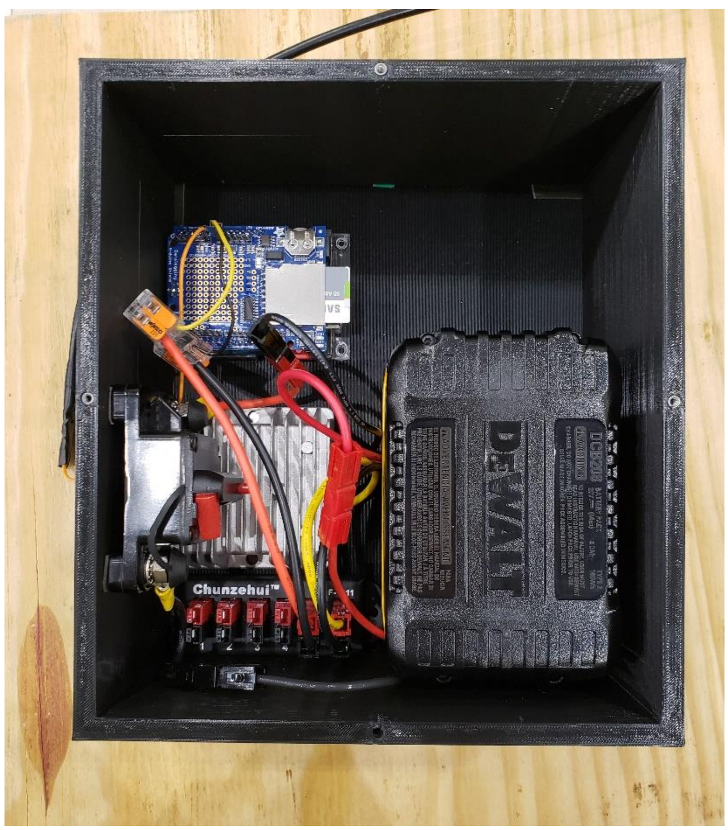


Figure 22. *Final Circuit Design*

As seen in the above figure, the battery and solar panel are both responsible for powering the Arduino Uno microcontroller. However, because the battery is rated for a voltage that cannot be distributed to the microcontroller, a buck converter was used to step down 20 V to 12 V. This was verified during the building phase using a multimeter. The solar panel produces 3.77 V, which was also measured using the multimeter. The switch is an efficient way to power off the circuit in case the battery is damaged or cannot be removed easily. Basically, it acts as a safety precaution. The microcontroller has a data logger attachment and is responsible for logging the data every 10 seconds. Currently, the only sensor attached is the AE sensor. However, this device is modular in the sense that there is a power rail connected to 12 V and ground that could act to connect more sensors. The idea behind this is to have a plug and play device where different sensors could easily be powered, grounded, and plugged into the microcontroller for signal. For the time being, there is not a use for it, but it could be necessary for future iterations.

The code for the microcontroller used starts with attaching the AE sensor to an analog pin on the device. For this particular iteration, pin A0, was utilized both physically attached to the microcontroller and attached virtually in the code. Then the AE sensor is set to be an input device since the microcontroller should be reading data from it and not writing to it. To connect the Data Logger Shield to the microcontroller, it will always be attached to pin 10 in the code as this is how the hardware of it was designed. The logger is considered an output device because data needs to be written on it.

The very basic steps of the algorithm include creating a file, which has an extension that can be opened easily in Microsoft Excel. Then for the file, it logs the amount of time that has passed since the program started in milliseconds, actual time and date from the RTC, and the AE sensor value.

There are quite a few safety precautions implemented in the code. If the SD card is not connected, the code will not run. If the data file could not be created, the code will also not proceed to run. The algorithm will also check for files with the same name, so data does not accidentally get overwritten. There is also a Real Time Clock (RTC) on the data logger. It is not detrimental to the data collection process if the RTC fails, but it will automatically be indicated in the data set after if the RTC does fail.

Another aspect of the code was deciding how often entries would be logged. The final decision was to set it to 20 milliseconds between each entry. This would reduce the amount of data points taken versus the original plan of having it log every millisecond. In addition, this makes sure the processor does not get overexerted from intense computation every millisecond. When the data is logged, this is considered volatile memory or short-term computer memory. It has not been officially saved in the hard drive until it is properly synced onto the SD card attached to the microcontroller. Because converting volatile memory to nonvolatile memory can be very power-demanding, the code is setup to sync every second. This delay does not pose a huge issue. It can only be problematic when it is critical to take the last second of data when the system is abruptly turned off. The baud rate that is the most comprehendible for seeing the response is 74880 bits per second which is set in the code. This value was determined through experimentation of trying different baud rates and seeing how the data response looks.

For the initial testing stage of this device, the location was in a controlled environment, done in an anechoic chamber. This helps ensure there are no other sound or electromagnetic waves present that could disturb the AE sensor as it takes data. The setup of the experiment can be seen below in Figure 23.

Figure 23. *Test Setup for AE Monitoring System*

The wooden board in Figure 23 represents a tree trunk with the right side being inside the trunk and the left side being outside the trunk. As the figure shows, on the right side, there is a funnel with a tube attached to the bottom of it. The tube represents a tree capillary that has water flowing through it. The funnel adds support for pouring water down the tube. The water inside the tube dispenses into a bucket at the bottom. This ensures that the water can be reused for other trials as well for purposes of not leaving any residue behind. On the left side of the figure, is the AE sensor taped down to the board on the opposite side of the tube. The end of the cable is taped down in addition to add support. The purpose of this test was to test the electronics in a complete circuit before including a housing for them. The AE sensor’s cable was long enough to exit the anechoic chamber. Therefore, the microcontroller was simulated to be at a distance away from the AE sensor as it would be in a real-world test case. This also allows for the anechoic chamber to be mostly closed during the testing phase, which helps the sensor’s accuracy.

In total, there were three types of tests done in the chamber. The first test being the control data of no response. The second was when the response was lightly hitting the wooden board. The third was pouring water down the tube. For the second and third tests, one of the team members was present in the room with the system while the microcontroller collected data autonomously from outside the chamber. Below are the results.

Figure 24. *Control Response*

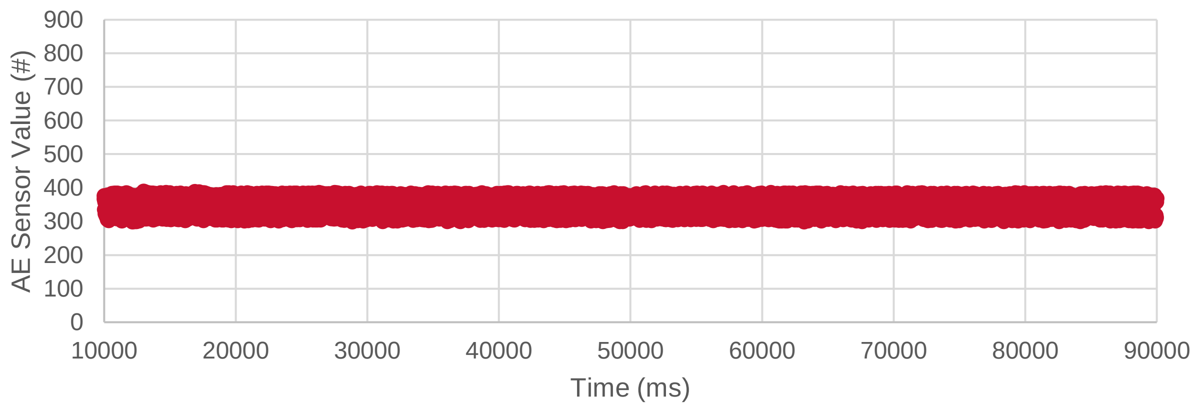


Figure 25. *Knocking Response*

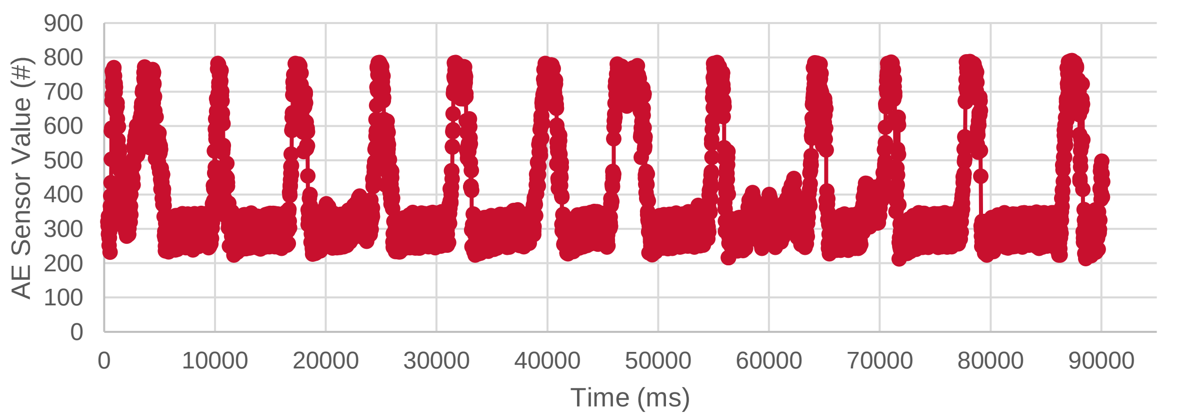
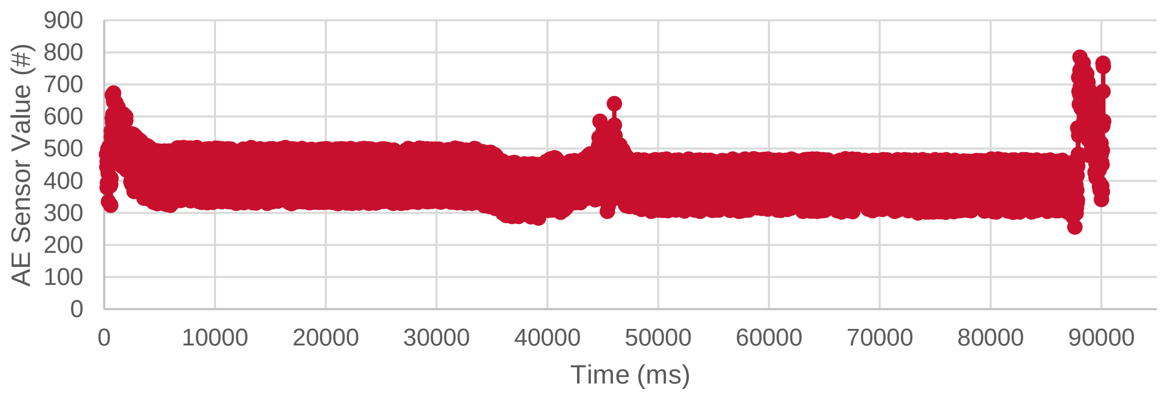


Figure 26. *Water Flow Reponse*



In Figure 24, it is clear that there is no response present when comparing to the other two graphs, and the baseline value for no acoustic emission response is roughly around 300 in amplitude. When analyzing Figure 25, there was a steady knock produced that created an acoustic emission response of about 800 in amplitude and head back down to 300 after the response has ended. For Figure 26, there were three points when water started getting poured. They have an inconsistent response as the amount of water starting to pour was different each time. To be more accurate in future test cases, a specific amount of water could be poured each time. This baseline does not quite steady at the amplitude of 300. It is within a range of 300 to 500 because water is slowly moving through the tube after being poured.

A future test case should be done outdoors on an actual tree especially during the springtime when the water flow within them is more active. Due to the time constraint, a weather resistant mechanical housing could not be manufactured to perform such a test case.

3 REALISTIC CONSTRAINTS

3.1 Engineering Standards

All information regarding the project is subject to the constraint of confidentiality, where the information learned, and design developed is property of the client and cannot be used by group members for profit.

3.2 Economic Constraints

The design is limited by the funding provided by the College of Engineering and Engineering Technology (CEET) and the client. As part of the senior design program at NIU, CEET provides $1000 in funding. Similarly, The Morton Arboretum is planning to provide the project with $1000. The total cost of the project should not exceed the total level of funding of $2000.

Since the client hopes to run multiple devices, they have requested that the cost per unit to be within a price range of $200-$500.

3.3 Environmental Constraints

The device is exposed to the elements during operation. To collect data for an extended period, it must be able to withstand the elements and persist through temperature change, strong winds, rain, and even snow. Similarly, the system will need to be well-enclosed to prevent tampering by local wildlife, both to protect the fidelity of data collection and the health of those animals.

3.4 Sustainability Constraints

The project's sustainability is one of its weaker areas, being a significant portion of plastics and non-renewables. In order to work around this, the parts are ordered from large companies, who can mass produce any item with ease and are more efficient as a result. However, one part that makes this project much more sustainable is the solar panel attached. The system is not entirely solar powered since the shade of the tree would often leave it without power but supplemented with solar to extend the battery life.

3.5 Manufacturability Constraints

This basis of this project being made of separate devices and easily buyable parts makes this entire device easily manufacturable. The client should be able to reproduce the device at not substantial additional costs and would easily be able to reproduce the software onto another device. However, if the manufacture were to be scaled up significantly the production would slow down, since the project largely relies on components bought from other companies and creates a significant bottleneck at larger scales.

This requirement affected the design by trying to make it as modular and reproducible as possible and allowing for custom changes in the future by the client. A few of these would be inevitable, but they must be well documented and easily done. The exact number of changes would be determined by experimentation. However, the devices are still built towards this goal with estimations of where it may be needed.

3.6 Ethical Considerations and Constraints

Ethical standards are widely studied and argued throughout engineering, with many being ABET or IEEE standards for various engineering subjects. These constraints largely affect the making of the device and basically affect the honesty of the maker, so these constraints are simple to follow.

A separate ethical concern is the usage of the device, whether it could be used unethically in any sort of way. This would pertain to misuses outright or crimes using this project. Since this is a research implement for tree study there is little chance of misuse and any crime committed with this is prevented by sticking to legal restrictions for the building in the first place.

3.7 Health and Safety Constraints

During operation, the electronics should not cause harm to the environment and those that interact with it.

3.8 Social Constraints

The social constraints of this project are little to none. The only major constraint is the idea that nature should remain natural, and this device should not be used. However, this device will improve this goal overall and is irrelevant to this project.

3.9 Political Constraints

Political issues would affect this project little, if at all. On a federal level there may be some budget differences based on who is in power, where the democrats have been interested in increasing funding for green initiatives, where Morton Arboretum may see additional funding. On a state level there was the “fair tax amendment” which was voted down funding would decrease on a statewide level, likely affecting grants towards the client, Morton Arboretum [27].

4 SAFETY ISSUES

Mechanical

With little human interaction with the device, the primary safety concerns are those with the surrounding environment. Mechanical failure of the housing can expose the electronics within and damage them. Similarly, if the adjustable strap on the housing fails, the device can fall to the floor and injure any animal or person standing near it. To prevent failure of the adjustable strap, they should not be overtightened during installation. The two-piece housing is secured by screws and ensures it will not come apart and expose the entirety of the hardware if the strap were to fail or a blunt force hits the housing.

Electrical

Exposed wires leading to the installed AE sensors could lead to an additional mode of failure. Ensuring that external wires are protected from the environment and animals ensures the wires do not short and no harm comes to any animals interacting with those exposed wires. Similarly, exposed wires could pose a threat to workers installing and removing the device. To prevent their failure from external means, the wires are wrapped in foil for water resistance and to help prevent animals from chewing through them.

Thermal

Failure of electronics could produce a spark and lead to combustion of the device and its environment [28]. The component of most interest is the Li-Ion battery. If the battery falls outside of its operating temperature of 10c to 55c as mentioned above, the battery could fail. The battery compartment in the housing will be insulated to help prevent such an event.

Biological

If damaged, Li-Ion batteries can leak. If the battery leaks, the fluid within can cause harm to users opening or moving the device and to any animals that contact it [28]. The watertight design is beneficial towards ensuring little to no battery fluid leave the device if failure were to occur. Whenever opening the device, it should be handled with gloves to prevent contact with any potential battery fluid.

5 IMPACT OF ENGINEERING SOLUTIONS

With the modular AE platform, the clients hope to examine the trees under their care from a new light and with additional depth. The ability to measure the sounds of physiological processes could provide more information in the study of those trees and in the understanding of how to manage them and oversee their health.

This new tool is an opportunity for the client to delve deeper into the inner workings of trees and hear them evolve in real time. By developing a multi-channel device, the AE response of physiological and structural activity within the tree is cross-referenced with environmental data through the microphone and geophone. The multiple streams of can allow the clients to study each tree more effectively, tying its changes to the environment.

Outside of the benefits to the tree itself, this acoustic study can also be used to measure trees' effectiveness as sound barriers to mitigate noise pollution from highways or other industrial sources. This could be beneficial to local communities that happen to be built around a highway or construction area. In addition, if trees can help with noise pollution, urban construction planning may incorporate more trees.

6 LIFE-LONG LEARNING

From both an electrical engineering and mechanical engineering perspective, we were never taught anything related to acoustic emissions in our coursework. Because it is the main focus of our project, we have been learning a lot about that topic and will continue to learn as our project progresses. In addition, none of our coursework requires biology much less the science behind trees. We are fortunate to have The

Morton Arboretum bridge this gap in knowledge during our meetings. Similarly, with acoustic emissions, as this project progresses, we will experience firsthand how to interpret the study of trees. This is beneficial to any of us in the future going into more of an environmental engineering, and one of our group members will be pursuing a career path in agriculture engineering.

Some new soft skills that we have acquired throughout this semester is working on a professional level with an industry partner. Not all of us were fortunate to have an engineering internship, so to get this interdisciplinary experience anyway is huge, especially in the aspect of combining engineering with biology. Having this connection could also lead to more opportunities whether it is with The Morton Arboretum or a similar research facility. Another soft skill that we all improved upon is communication. During a pandemic, it can pose a challenge communicating virtually. Being in a professional video call is not something any of us has experienced until this pandemic. While there are technical difficulties here and there, we are learning to grasp the format from our weekly meetings with our teacher's assistant and faculty mentor, bi-weekly meetings with The Morton Arboretum and our preparation for the final presentation.

More on the lines of an interdisciplinary experience, our team dynamic is two electrical engineers, one being a double major in computer science, and a mechanical engineer. We can utilize three different department's coursework and skill sets for this project as well as learn from each other. This is a great teamwork opportunity that really is preparing us to work in industry since teams will almost certainly be interdisciplinary.

For technical skills, this project is heavy on the electrical side, and our mechanical engineer will get to step out of his comfort zone and help with some of the electrical wiring. He also has the challenge of designing his mechanical components around the electrical components.

7 BUDGET AND TIMELINE

7.1 Budget

Table 2: *Senior Design Budget*

Item	Quantity	Cost Per Part	Subtotal
Arduino Uno	1	$23.00	$23.00
Adafruit Assembled Data Logging Shield	1	$14.99	$14.99
Data Logger RTC Battery Cell	1	$4.97	$4.97
MicroSD Card 32 GB	1	$10.99	$10.99
SparkFun Solar Panel	1	$39.00	$39.00
DeWalt Battery Charger	1	$24.99	$24.99
DeWalt 20 V Max 8000 mAh Battery	1	$144.99	$144.99
DeWalt Power Adapter	1	$15.98	$15.98
AE Sensor	1	$665.00	$665.00
Accelerometer	1	$8.99	$8.99
DC to DC Voltage Converter	1	$17.99	$17.99
Circuit Breaker	1	$26.50	$26.50
Silicon Wire	1	$15.48	$15.48
Anderson Connectors	1	$12.99	$12.99
Anderson Crimper	1	$35.99	$35.99
680K Ohm Resistors	1	$6.49	$6.49
200K Ohm Resistors	1	$6.49	$6.49
Microphone	1	$6.95	$6.95
Geophone	1	$59.95	$59.95
Header Pin	1	$4.99	$4.99
Vibration Sensor	1	$7.99	$7.99
Raspberry Pi 4 Model B	1	$35.00	$35.00
Raspberry Pi 4 Power Supply	1	$11.99	$11.99
Raspberry Pi MicroHDMI to HDMI Adaptor	1	$9.99	$9.99

Raspberry Pi 4 Case	1	$8.99	$8.99
Arduino USB 2.0 A Male to B Male	1	$2.99	$2.99
Stainless Steel Inserts for Plastic	1	$7.51	$7.51
Screw	1	$2.70	$2.70
Black Polypropylene Filament	2	$40.00	$80.00
BNC Cable	1	$9.99	$9.99
BNC Scope Clip	1	$9.99	$9.99
BNC Connector Female to Female	1	$5.95	$5.95
		Total:	$1339.81

From The Morton Arboretum, Center for Tree Science, a provided $1000 was given to this project. This project was also awarded $800 from Enhance Your Experience (EYE) Grant, sponsored by the Northern Illinois University Honors Program. Table 2 above shows the quantity, price, and subtotal of each component for the project.

$53.95 was used for purchasing the computing portions of our system, which are the Arduino Uno, Data Logging Shield, RTC Battery Cell, and MicroSD card [18] [19]. Unlike the acoustic emission sensors, these products are produced in abundance. This is contributed from their wide range of uses and popularity, making the pricing reasonable for consumers.

$224.96 was used for power supplies, which included the DeWalt Li-Ion battery, battery charger, solar panel, and battery adapter [7] [20]. In addition to this, $121.93 was used for circuit building materials such as silicon wires with the proper gauge to withstand 20 V and a circuit breaker.

As for the microphone, they do range in pricing depending on the size. Some can be cheap while others can be on the pricier side. For this project's purpose, a small one was purchased for $6.95.

Like the acoustic emission sensors, geophones are not frequently used and therefore, they are not in demand within the marketplace. There is only one that meets the needs of the project, and that is the SM-24 Geophone sold by SparkFun [26]. The pricing on one is $59.95. This is on the pricier side of microcontroller sensors, but it is also the lowest priority of this project. In addition, the geophone is currently listed as backorder. Therefore, this amount may be reduced in the future depending on what gets implemented into the system.

Accelerometer breakout circuit boards are easily obtainable, and three of them in a bundle cost $8.99 altogether. From a teamwork standpoint, getting three for cheap is the perfect number to have each team member work with one.

For the 3D-printed housing, $80 was spent on two spools of polypropylene filament. This allowed for faster prototyping and device development. Also, $60 was used on mechanical hardware needed to stabilize the design.

7.2 Timeline

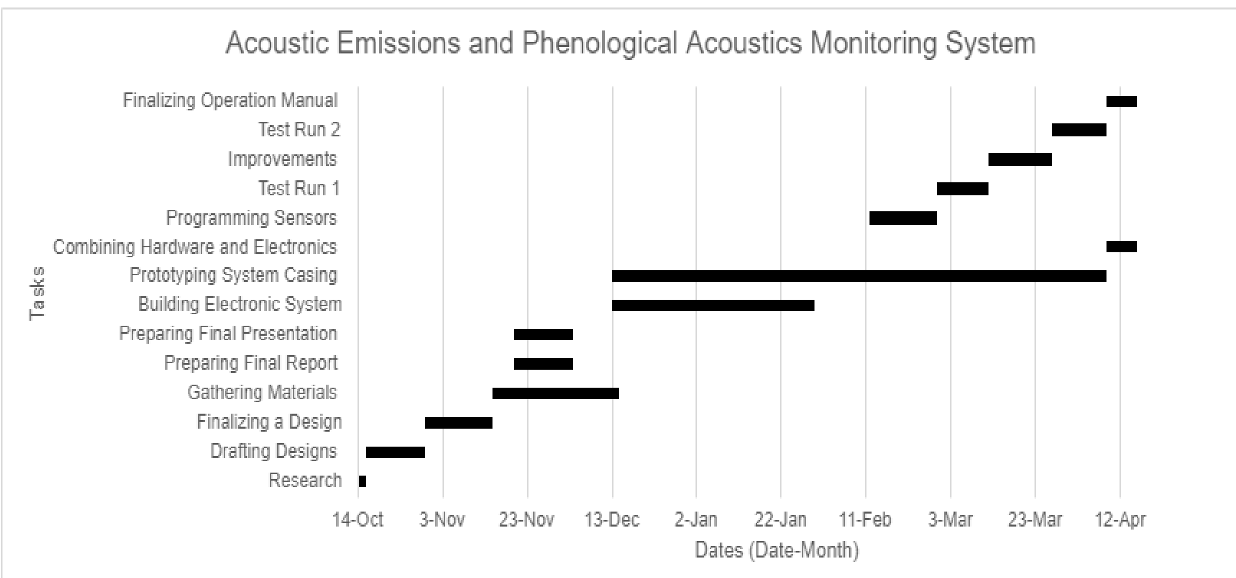


Figure 27. *Project Schedule*

From Figure 17, the largest setback for the project is getting the system casing 3D printed and prototyped. The electronics side of the project was finished far before the mechanical side was. Due to this, there was not a whole lot of time to combine the electronics and mechanical housing to the most optimal prototype. For the Test Runs, they were performed with just the electronics in a controlled indoor environment.

8 TEAM MEMBERS CONTRIBUTIONS TO THE PROJECT

8.1 Team Member 1

Esteban Molina Hoyos handled the mechanical design of the device throughout the design process, developing it to fit different designs. Similarly, multiple support mechanisms and application methods for the device were explored and iterated upon. He also researched and selected the manufacturing method and material choice for the design.

He designed and built the AE and electrical sensor housings, as well as made revisions and comment on their future iterations. He assisted in troubleshooting and testing of the AE sensor and its associated electrical circuit.

8.2 Team Member 2

Charles West in charge of researching the microphone, geophone, and solar power options. So, he wrote about these sections in the papers alongside their specific usages and limitations. He then led the research, alongside Theresa, into the power draw and limitations of the device. This led to discoveries that were instrumental in readjusting the design to last the client’s requested lifespan of one week between charges.

This semester he worked alongside Theresa with the electrical side of the project, soldering parts and building elements of the circuit. And he worked on testing and prototyping the device with associated microcontrollers and oscilloscopes.

8.3 Team Member 3

Theresa Li was responsible for the research on the AE sensor, microcontrollers, and power supply. Logically, she took over these sections of the papers as well. After collecting component information from everyone, she designed the circuits for all three of the alternative designs and the final optimal design.

This semester, she spent the beginning of it creating purchase orders for all the necessary electronics of the project. Then she began to build the circuit needed and programmed the microcontroller. Afterwards, she did some test runs for the acoustic emissions sensor.

9 CONCLUSION

From this effort, the specifications of the different types of acoustic emission sensors are becoming clearer of what is needed for this system. The selection process was narrowed down to a very low frequency, stainless steel, acoustic emissions sensor with a preamplifier and the convenience of having a pre-existing wire attached to the BNC connector. As for microcontrollers, there are many different types out there, but due to the constrained timeline of the first iteration of this project, it would be more efficient for the system to use a microcontroller, capable of a high-level language. An Arduino Uno with attached storage fits this description.

Sensors within this device were chosen carefully, as it was the vital component of the structure. For the system's purposes, the microphone does not need to be a super sensitive, high-tech microphone. Therefore, it was decided that the microphone used would be a simple component microphone that can attach to the analog spots on the Arduino as well as an accelerometer to complement it. The geophone is an optional component that aids in listening to the roots of the tree and the SM-24 is well suited for Arduino usage. A waterproof 3D-printed polypropylene housing is set to enclose the suite of electronics necessary for the collection of AE and environmental acoustic data. As part of the housing, an integrated sound conductor driven into the flesh of the tree is present. 3D printing the housing helps with rapid prototyping and fitting the components into the desired form factor. When installed, the housing is supported by an external post anchored into the soil. All these components work together in this AE monitoring system to further research in predicting the health of trees through acoustic monitoring.

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12 APPENDIX

12.1 Supplemental Material

The Morton Arboretum is a public garden and outdoor museum in Lisle, IL. Moreover, they also have a Center for Tree Science, and this is the department supporting the project. The mission of the Center for Tree Science is to research and develop ways to sustain trees.

13 Theresa Li's Honors Capstone Experience

For my individual contribution to my capstone project, I was in charge of figuring out how an acoustic emissions sensor works as this is the core sensor of my project. I spent the Fall semester researching what AE sensor would be best suited for our client needs. After deciding which sensor, the other parts of the circuit came into place as I designed everything around the sensor. In early January, the parts were ordered. I did the majority of the electronic circuit wiring. The project was fully assembled at the end of February, and after that, I was in charge of testing the project. I spent quite amount of time testing in NIU's Digital Signal Processing Lab's anechoic chamber.

Completing an honors capstone has helped me gain real-world experience in the engineering field as this was a project proposed by Morton Arboretum's Center of Tree Science, an outside client of NIU. It taught me a lot about how much planning and preparation goes into designing a functional product. This is not something I could typically learn in the classroom. The courses I took gave me the knowledge and the ability to think like an engineer, and this capstone taught me how to apply my knowledge like an engineer.